NISTIR 90-4271

HIERARCHICAL REAL-TIME CONTROL TASK DECOMPOSITION FOR A COAL MINING AUTOMATION PROJECT

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HIERARCHICAL REAL-TIME CONTROL TASK DECOMPOSITION

for a Coal Mining Automation Project[1]

Hui-Min Huang
Mechanical Engineer
Robot Systems Division
National Institute of Standards and Technology

March 24, 1990

[1]Sponsored by the United States Bureau of Mines under Interagency Agreement (Agreement No. J0189027). The project is titled "Architecture for Internal Control of Mining Machines". The primary role for the Robot Systems Division of the National Institute of Standards and Technology is to act as consultants in the area of real-time control system architecture.

Contents

ABSTRACT

This paper describes a systematic approach to hierarchical task decomposition and planning. In particular, the methodology can be used to design a complex system which receives goals from the external world, performs intelligent planning, and commands the actuators to achieve the goals. This document was written as a part of the "Architecture for Internal Control of Mining Machines" project.

ABBREVIATIONS

Bureau of Mines	BOM
Bureau of Mines Communication Network	BOM/NET
Continuous Miner	CM
Elementary Move	E-Move
Executor	EX
Job Assignment Module/Manager	JA
Mining Automation Standard Reference Model	MASREM
Mobile Control Structure	MCS
National Institute of Standards and Technology	NIST
Planner	PL
Real-Time Control System	RCS
Sensory Processing	SP
State Transition Diagrams	STD
Testbed for Autonomous Mining Machine Experiments	TAMME
Task Decomposition	TD
World Modeling	WM

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1. Introduction

The Mining Automation Standard Reference Model (MASREM) adapts the the National Institute of Standards and Technology's (NIST) Real-Time Control System (RCS)[Al 82][1] architecture to coal mining. The basic model behind the RCS technology is the intelligent machine system, as shown in Figure 1. The intelligent machine system has sensors that detect external events, and actuators that execute planned tasks to achieve the system's goals. The Sensory Processing modules perform filtering, correlation,and integration functions so that external world features and situations can be extracted. The Task Decomposition modules decompose and execute the system's goals. The World Modeling modules store information, answer queries, evaluate situations and make predictions. The MASREM is a hierarchical architecture.

Volume I of MASREM [Al 89] was developed to define the overall conceptual framework of the hierarchical architecture for the mine automation control system. The functional hierarchy, as shown in Figures 2 and 3, contains seven control levels. Each level has multiple subsystems[2]. Conceptually each subsystem has three functions: Sensory Processing, World Modeling, and Task Decomposition, shown in Figure 4. It would be an enormous task to design a full system. Therefore it is essential to use specific examples to illustrate the application of RCS, so that interested parties can pursue an incremental implementation and integration towards a complete system.

This paper addresses key issues of the Task Decomposition function of RCS. The overall control architecture developed in this paper is generic and therefore may be applied to any mining operation. The emphasis here has been placed on a Joy 16[3] CM continuous mining

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[1] Denotes the references listed at the end of this paper.

[2] In Figures 2 and 3, all blocks are subsystems to their parent blocks (except for the highest block).

[3] The Joy 16 CM continuous miner has been used in the U. S. Bureau of Mines laboratory as a test bed, referred to as TAMME, or the Testbed for Autonomous Mining Machine Experiments. BOM has also purchased a Joy 14 CM machine and it will be put in the Marrowbone Coal Mine in West Virginia for experiments. On the Joy 14 CM; the BOM/NET system, the next generation to the TAMME, is being implemented. There are slight differences in the machines' capabilities, as well as the control and communication mechanisms, between two models. This paper started by basing itself on the Joy 16 CM setup, and gradually shifted to the evolving BOM/NET. Necessary modification, such as the machine activity definitions, may still be needed, and will be made in the future. But this would not affect the discussion of the Task Decomposition Methodology.

AN INTELLIGENT MACHINE SYSTEM

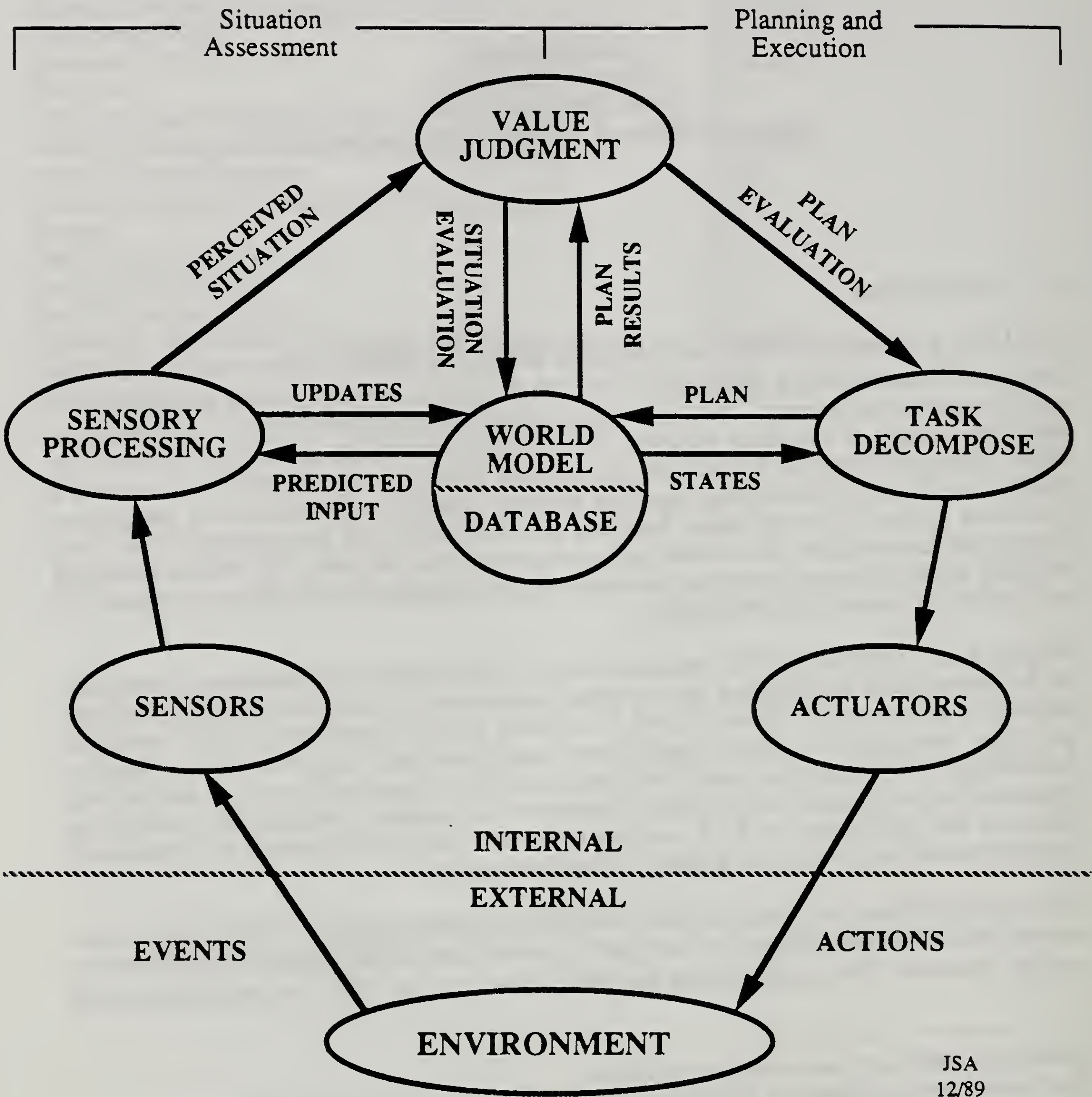


Figure 1 The Model of an Intelligent Machine System

MINE AUTOMATION HIERARCHICAL REAL-TIME CONTROL SYSTEM

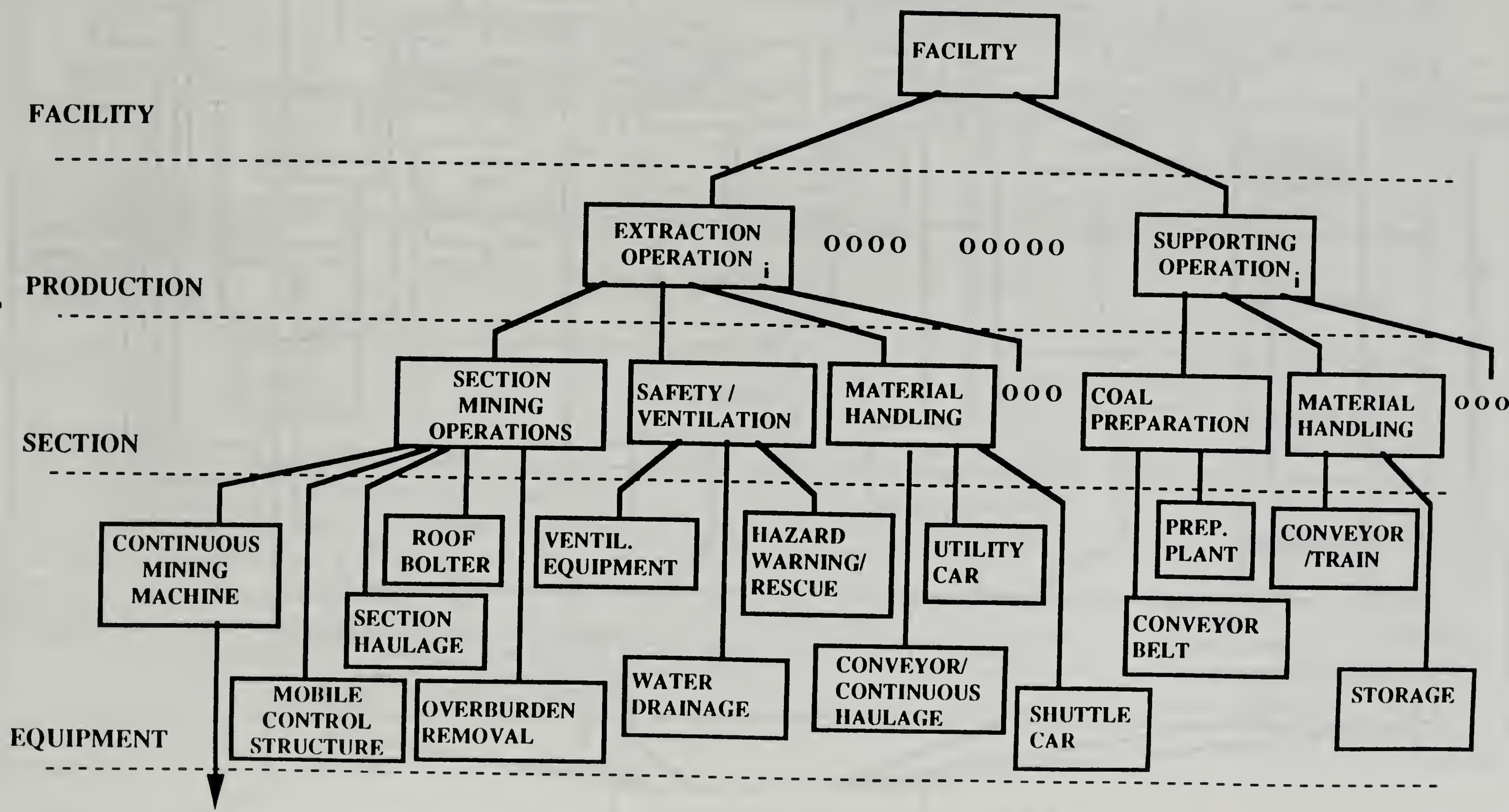
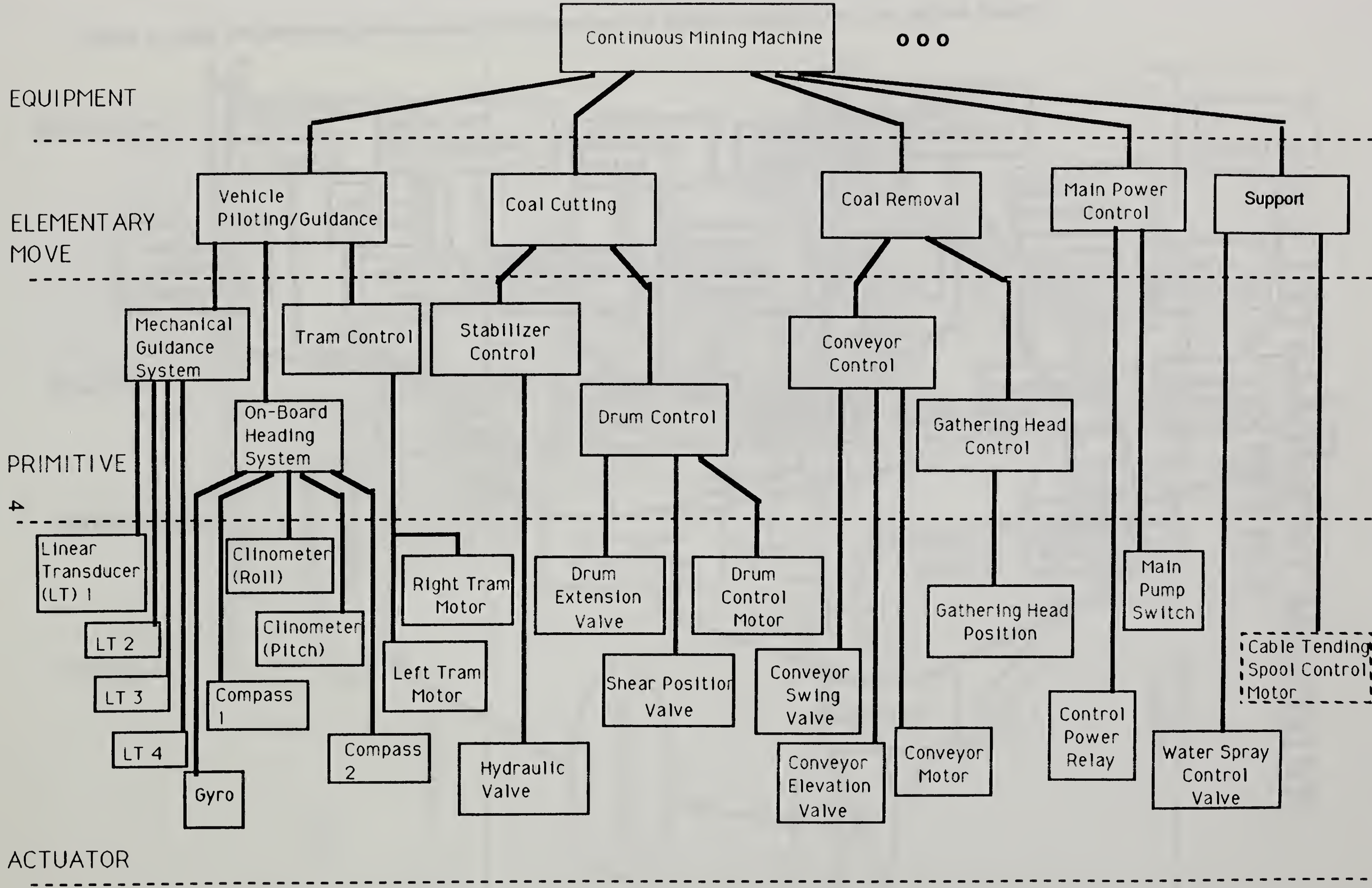


Figure 2 Mine Automation Hierarchical Real-Time Control System Architecture (for Higher Levels)



Note. Functional Decomposition may change if continuous haulage is used; for example, the Cable Spooling Control may appear on the haulage unit rather than shown here as a manually controlled support function.

Figure 3 Mine Automation Hierarchical Real-Time Control System Architecture (for Lower Levels)

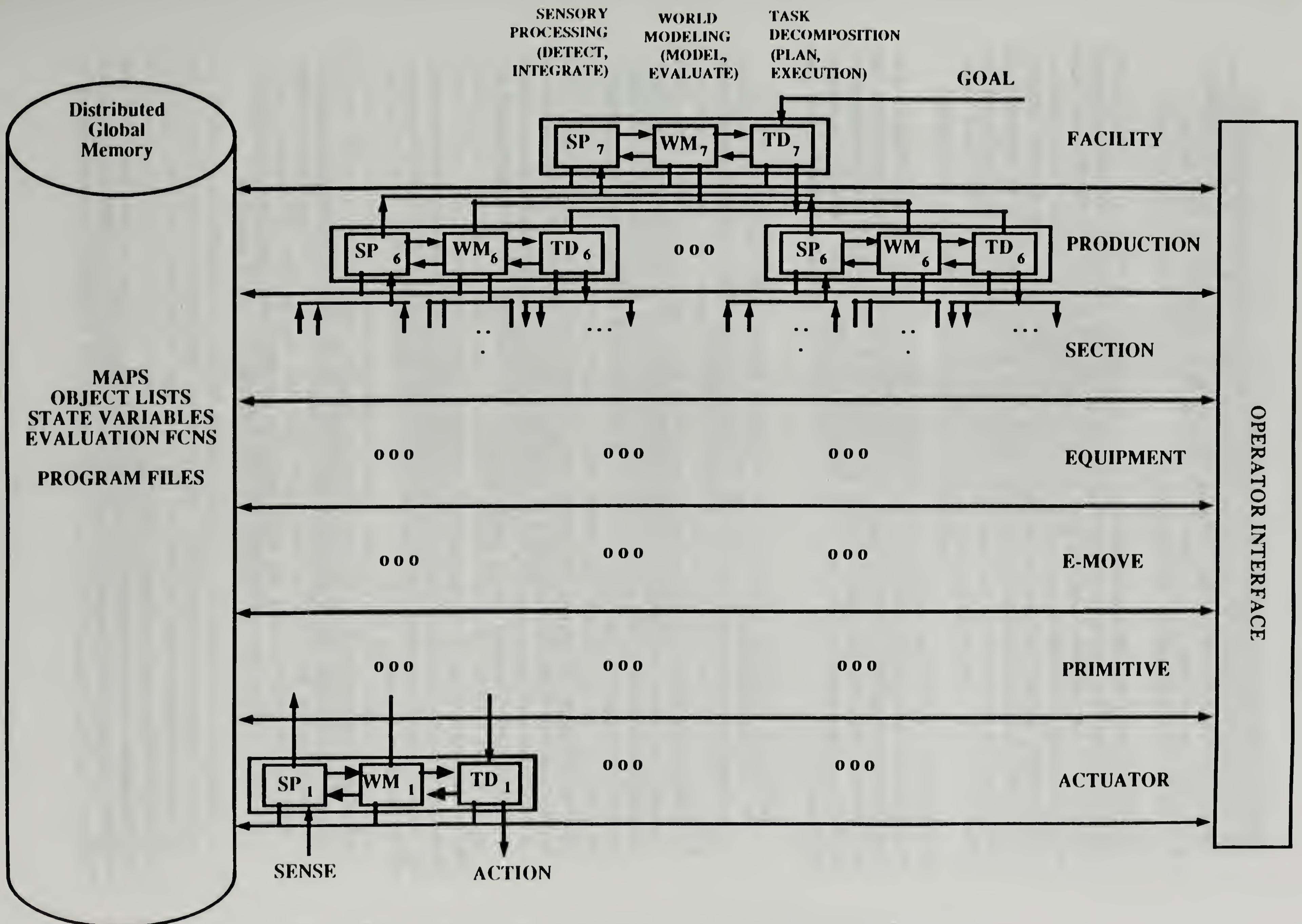


Figure 4 Real-Time Control Architecture Functional View for Each Subsystem

machine[4] (reference to a company's or a product's name is for identification only and does not imply government endorsement) [Jo 82], as this is in line with the current research focus of the United States Bureau of Mines (BOM), as is outlined in [Sch 89-1][5].

2. Task Decomposition Methodology

The RCS Task Decomposition function is responsible for planning and executing the decomposition of goals and/or tasks at each level of the system's hierarchy. An RCS intelligent control system interacts with the environment at its highest level, it receives a compound goal, and at the lowest level acts on the environment to achieve the goal. Internal to the system, hierarchical and heterarchical task decomposition, as well as temporal and spatial task decomposition are occurring. 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".

In designing an RCS, the definition of context is the first task. This task includes the establishment of the system's objectives, the problem domain, the constraints, and the overall assumptions. The task must also include a narrative description of the approaches to achieve the goals and the system's typical scenarios to be performed. Once the context is defined, the design of the system's Task Decomposition can be approached by the following steps:

* Develop a Functional Hierarchy. The first step in setting up the basis for development of task decomposition is a structure that takes into account the system's goals, the environment, the existing facility, and other constraints.

* Perform Task Analysis and Develop Task Commands for Each Subsystem at Each Level. Answers to the following questions must all be specified: what can each subsystem perform, what are the constraints, and what information is required in order to perform a given tasks?

* Develop State Transition Diagrams. Task commands defined above are used to develop State Transition Diagrams to describe how higher level tasks are decomposed into lower level tasks, and how the constraints for the commands are implemented as transition requirements among different states.

The following steps can be considered as the second stage of task decomposition, since their objective is to process the machine intelligence developed in the previous three steps. This second stage of task decomposition will not be discussed in this paper at this time but will be presented in another paper.

* Design Algorithms and Establish Requirements for the Job Assignment Managers, the Planners, and the Executors. The software modules that perform spatial decomposition and conflict resolution (the Job Assignment Managers), that hypothesize future actions and select or derive specific plans (the Planners), and the software modules that execute the plans (the Executors), must be specified.

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[4] See [Pa 88] for different types of continuous mining machines.

[5] The document also outlines the objective of using a continuous haulage system, as opposed to the use of shuttle cars, to transport coal to the main conveyor system. This paper includes the discussions for both vehicles.

* Develop Interface Specifications for the Integration of Task Decomposition with the World Model. The world model responds to TD queries (as described in MASREM Volume I) of the form 'what if' and 'what is' questions. It is necessary to lay out all state variables and the queries, so that the world model can be designed to support the Task Decomposition function.

The above five steps are tightly coupled. The guidelines for developing the functional hierarchy (Section 3) establish the basic functional requirements for each subsystem within each level, which will be used to define the system's activities (Section 4). The task commands and constraints developed are basic elements to develop intelligent plans (Section 5). Likewise, all the results developed from Sections 3 through 5 dictate the requirements for the processes (the job assignment module, etc.) that execute the plans, they also dictate the world model support requirements.

3. Functional Hierarchy Development Guideline

A functional hierarchy, Figures 2 and 3, lays out all the necessary functional modules (as well as subsystems) and the relationships among them. There are different methods for constructing such a hierarchy. The following is a guideline for developing an RCS functional hierarchy. The guideline also defines some basic functional requirements for each level and each subsystem.

3.1 Autonomy and Modularity

The RCS methodology emphasizes maximizing the autonomy and the modularity of all subsystems. To achieve subsystem autonomy and modularity, the functional hierarchy is developed so that each process (such as the tramming function in the Primitive level, the CM entity in the Equipment level, or the Sectional Mining Operation in the Section level) will have a closed loop at the lowest possible level. By doing so, the independent (autonomous) subsystems are formed. Each subsystem contains explicitly defined modules with clearly defined inputs and outputs. Subsystems may themselves be composed of several hierarchical levels. Each level of subsystem decomposition includes: sensory information input, data storage, data manipulation routines, state space models, control laws, and output commands. Each sensor and actuator 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 band-width decreases about an order of magnitude per level. Therefore the autonomy and modularity guideline promotes self-sustained modules, locally maximized communication traffic, as well as extensibility for a system.

By closing the loops at the lowest possible levels, changes on one module would have minimal effect on other modules, but communication among modules is still provided for. Without this autonomy and modularity approach, data queries may logically pass through longer routes [Hu 90-1].

3.2 The Bottom-Up Approach versus the Top-Down Approach

The autonomy and modularity guideline referenced above is one reason the development of an RCS application often starts with the lower levels. Each autonomous module is used as a building block and therefore the system is built up from the bottom. Another reason for the bottom-up approach is that the lower levels are either more closely related to or directly use the actuators and the sensors to interact with the environment and in turn tend to be the near term project objectives. But on the other hand, the development of a system from the top down also has advantages. One advantage is that generic assumptions and overall strategies for certain major operations can be established up front for easier reference. For example, the task analysis in Section 4 uses a bottom-up approach: the description and the assumptions for the 'CM to align to the haulage unit' command is not seen until Section 4.4.5, the Equipment Level. Therefore the discussions of the corresponding lower level commands (such as 'conveyor swing', 'conveyor boom setting', 'coal load', etc. as appeared in the Sections 4.4.2 through 4.4.4), must refer forward to Section 4.4.5 frequently.

3.3 The System's Goals

The goals for a system determine the top level of the hierarchy. Since from NIST's point of view, the ultimate goal for the industry is to have an functionally integrated coal mine, therefore a Facility Control Level is required as the highest level for the control system, as shown in Figure 2.

3.4 Pre-Defined Functional Requirements for Each Level

In the RCS methodology, each level has specific functions that it performs [Al 88, Al 87]. These levels from the bottom up are:

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

* Level 2 -- Primitive Level: The primitive level is the dynamic control level. The pre-defined task decomposition function for this level deals with all the dynamic computations, such as computing the maximum allowed time for a commanded CM shearing angle. The sensory processing function includes sensory fusion from individual sensors and sensory data integration, which produces linear features for objects.

* 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 forces causing the motion and the mass of the bodies differentiates the kinematics from the 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 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 object surface features, 3-D object distance and relative orientation, etc.

* Level 4 -- Equipment Level: The equipment level includes subsystems representing physical entities (e.g., a Mobile Control Structure). However, there are physical entities that have only very simple functions. These functions can be modeled as E-Moves belonging to equipment which is functionally closely related. Multiple simple functions can also be combined together to form a more significant physical entity which can be modeled as a subsystem in the Equipment

Level. At the Marrowbone Coal Mine in West Virginia, scoop cars combine the functions of cleaning coal, spraying rock dust on mined surfaces, and supply transport.

Tasks coming down to the equipment level are defined in terms of single pieces of equipment on single target objects (as compared to object surface features at the E-Move Level).

* Level 5 -- Section Level: The section level subsystems perform coordinated group functions (in other RCS applications this level is referred to as the 'Group Level'). For example, the Section Operation subsystem and the Material Handling subsystem have tasks involving multiple pieces of equipment.

* Level 6 -- Production Level: The production level is an additional level created for systems either having tasks complex enough to require an extra step 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 functional hierarchy, it is envisioned that several extraction operations may be running in parallel in a large coal mine, and each would need a 'set' of all Section Level subsystems.

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

3.5 Existing Facilities and Resources

The NIST research effort, as part of the U. S. Bureau of Mines underground coal mining automation research project [Sch 89-1], must utilize existing equipment (the CM, LaserNet, gyroscope, clinometers, etc.) -- this implies the existence of certain Equipment and Actuator Level subsystems. Other existing resources include software, such as BOM/NET [Sch 88] communication protocol and the expert system machine diagnostic systems [Mich 89]. As the system development effort evolves, software reusability and generic software components may become significant concepts in handling existing software resources.

3.6 Operation Requirements and Functional Coherence

The closely coupled face area operations in a coal mine dictate the need for a Section Mining Operation subsystem in the Section Level to coordinate operations such as, coal cutting (performed by CM's), coal haulage (performed by shuttle cars [Jo 81] or continuous haulage units), bolting, etc. (those being coordinated are actually subsystems of the next lower level, as shown in Figures 2 and 3). In another example, the Elementary Move Level is developed by observing the major operations of equipment, such as the CM. The CM would have the following subsystems: the piloting/guidance, the coal cutting, the coal removal, the main power supply, and the support, as shown in Figure 3.

3.7 Concurrent Computing Timing Requirements and Software Module Sizes

As described in MASREM Volume I, cycle time may increase by a certain factor (typically five or ten) from any lower level to its nearest upper level. This implies that the software modules will have computation time constraints, which in turn affect the hierarchy development. The synchronization requirements would also affect the hierarchy development. For example, in the CM, the fact that the stabilization jack could be down before the cutting drum cuts the coal implies these operations should be parallel subsystems belonging to the same parent subsystem, therefore frequent synchronization will be required.

3.8 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.

3.9 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.

3.10 Contradictions

Violations can be seen when different guidelines are applied simultaneously. For example, the BOM's laser system is used to provide range data for the CM, but it is physically located on the Mobile Control Structure (MCS). The MCS has been defined as an Equipment Level subsystem in an RCS structure (parallel to the CM subsystem), which is consistent with the "pre-defined functional requirements for each level" guideline -- but it violates the "autonomy and modularity" guideline for not closing the piloting/guidance function control loop at the E-Move level. The CM Piloting/Guidance E-Move subsystem has to get range information through the Section Level (a longer route) which coordinates the CM and the MCS.

3.11 Achieving Automation Through Integration

It is desirable for a coal mining control system to have a functionally distributed but integrated architecture[6]. This is largely due to the environment and the existing hardware and software constraints. A mine facility may have multiple extraction operations running concurrently and numerous pieces of equipment spread throughout. Each would have its own local controller and would be connected by certain network schemes. In addition, there has been major development work at many institutions, such as the Bureau of Mines, Carnegie Mellon University, and West Virginia University, and from this work resources in the form of software/hardware will be produced. A key to automation is to have a comprehensive system architecture to integrate these resources. Such an architecture must be designed for the mining industry. MASREM, as a generic conceptual architecture, can serve this purpose.

There are several ways to integrate a reference architecture in work developed by multiple institutions. One is to have all the work conform to one such structure. A more flexible approach is to standardize on interface formats and on required interface information (according to the functional requirements proposed by the reference architecture). The reference architecture can then be used to check and ensure the existence of all necessary functions from a system's point of view, so that there will be no missing pieces in the resulting system.

For the MASREM to be a mining automation reference architecture, the flexible integration approach includes (a) consistent data modeling, particularly regarding a dynamic mining plan representation, (advantageous in that it helps to facilitate easy data communication); (b)

[6]A central processing computer may be needed for the Facility Control Level.

sharing the same design concept, such as having a distributed World Model to compute the best estimated world states to enable response to Planner/Executors' queries, or by having Planners that plan, update, and prioritize task commands; and (c) establishment of the interfaces between systems developed by other researchers and the various subsystems in an RCS architecture. In this approach RCS is a conceptual structure for all the essential functional elements in an integrated coal mining system, and is used as a systematic approach in designing such a complex system. By this approach, a distributed but integrated system architecture can be developed. The West Virginia University's Face Decision Support System (FDSS) [Nu 88] and Mine Management Support System (MMSS) could serve as high level decision support modules in an RCS structure by interfacing them with various RCS modules at appropriate levels. The Bureau of Mine's BOM/NET, for example, will serve as the RCS Actuator Level (their interface is discussed later in Section 4). In Figure 5, a distributed hardware configuration is shown containing several sections.

4. Task Analysis and Task Command Lists

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 in the higher levels) have to be defined specifically by means of a complete list of task commands. Each command is described later in this Section and again using State Transition Diagrams (STD) in Section 5. 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. Any mining plan or mining scenario developed can then be described by the task commands and by the State Transition Diagrams.

4.1 Problem Domain

Task analysis seeks to resolve the following questions for a system (including all of its subsystems in each level): what tasks are implied, how can these tasks be performed within, and what are the requirements and constraints of the system. For example, what is the capability of a CM? It can perform a cut operation. How does the CM do it? A cut implies a series of sump-shear-trim (refer to Section 4.4.4 for command definitions) cycles. What needs to be done prior to a cut? Functions to be performed include the processing of the target distance calculation, the engagement of the haulage units, etc.

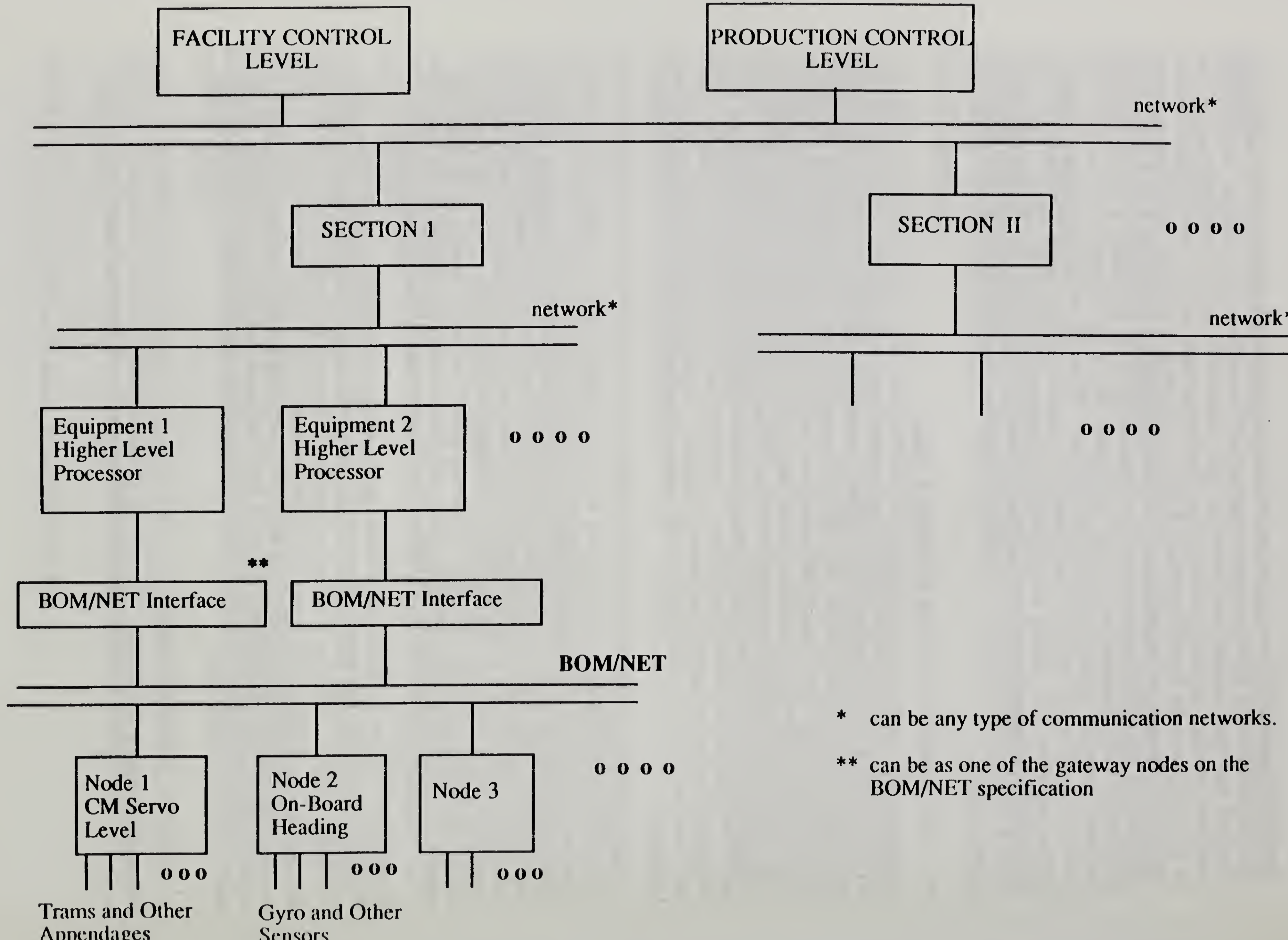
In particular, when multiple subsystems are involved, the complexity of cooperative behavior makes the definition of system and individual machine activity even more necessary.

As discussed in Section 2, the guidelines for the functional hierarchy development set up the basic functional requirements for each level and each subsystem. These functional requirements are the basis for task analysis. In performing task analysis, the following issues should be considered:

4.1.1 Spatial Coordination Strategy

For example, how does a shuttle car or any other haulage unit align itself with a continuous miner?

MINE AUTOMATION HARDWARE CONFIGURATION



* can be any type of communication networks.

** can be as one of the gateway nodes on the BOM/NET specification

Figure 5 Mine Automation System Hardware Configuration Concept

4.1.2 System/Machine Capability Definitions and Assumptions

There are two types of information characterizing an automated machine:

* Behavioral Characteristics: what commanded operations can it perform;

* Physical Characteristics: machine dimensions, tramming speed, boom reach, etc.

This paper focuses on the first issue. A 'sump' is defined here as the tramming of the continuous miner (CM) into the coal face for a distance of less than the drum diameter. But physical characteristics are only symbolically defined in this paper. For example, 'CM_nominal_length' can be equated to '38.7 ft.' later in the coding stage, and therefore it is of less concern in this paper, unless it effects the behavioral performance (e.g., in handling activity synchronization, the actual speed may be included in discussion).

4.1.3 System/Machine Intelligence Level

* 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 would also be necessary when the system does not approach the goal as expected by using the preselected plan. On the other hand, a more primitive format for task planning, which is not regarded as real-time planning, is to have pre-defined scripts. Capabilities such as plan selection and replanning may not be available. Whereas script planning might serve as a first step in approaching automation, real-time capabilities involving replanning are ultimately sought.

* the Emergency Reaction Capability of Each Machine When Encountering Unexpected Problems:

  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.

4.1.4 Coordinate Reference Frames and Resolutions

In general, at the higher levels, a global coordinate frame is used, and in the lower levels, machine centered local frames are used. In a global frame, further subclassification in terms of resolution are possible for different levels. Therefore successive transitions in coordinate frames or resolutions can be seen among different hierarchical levels. A mining operation can be referenced by the production tonnage at the highest level. It is then decomposed to and is referenced by, at a lower level, a certain area of one coal seam to produce the coal. At another lower level, the mining plan is referred to as certain coordinates to cut. At even lower levels, the mining sequences are referred to as the number of cuts to make, the number of sumps to make, all the way down to the amount of tram motor current for the distances involved. The third axis (the Z axis) is referred to at the higher levels as 'shear down some number of feet', this is then transformed to 'degrees of shearing angle' and 'initiate shear at angle' at even lower levels. Another example would be, in dealing with the machine heading: '45 degrees' means northwest in the higher levels, but may mean counter-clockwise 45 degrees relative to last heading in the lower levels (refer to Figures 6a-c).

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. Therefore developers should be made aware of this coordinate transform and put it in place.

4.1.5 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 (referred to as the Elementary Moves, or 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 compared to this Level's inputs, but they are all with the dynamic characteristics attached to them (refer to Section 4.3.2 for the issue of conformity to the BOM/NET protocol design). The Actuator Level will convert primitives to action commands, such as opening a pilot valve to pressurize the cutting head hydraulic system, so that the shear operation can be activated. The valve will be closed when the desired shear angle is reached.

4.1.6 Existing Constraints, Existing Practices, and Flexibility

As discussed in Section 3, under "Existing Facilities and Resources", 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, therefore the activity definitions for them can be viewed as the descriptions that conform to the existing capabilities. Examples can also be seen in the Primitive Level, where the Joy 16 CM Tram Control can have only twelve hard-wired commands. Another part of existing constraints are regulations. For example, in the Section Level, ventilation has to be set up before the CM equipment can operate at the coal face, therefore these two task commands must have synchronization built in[7].

Existing mining practice may be used as a reference to identify task commands. For example, the sump and shear cycle is such a typical mining practice and corresponds to the sump and shear commands described in MASREM. But the MASREM does not intend to entirely follow the existing practice. The RCS "Section Mining Operation" (Figure 2) subsystem is responsible for fewer pieces of equipment than a section foreman. The distinguishing criteria is the computing efficiency versus human control efficiency.

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[7]Besides the existing constraints, designers are give flexibility to define task commands.

All these issues (from Sections 4.1.1 to 4.1.6) must be addressed by the establishment of the task commands. The format, the parameters, and the description for each task depict the requirements.

4.2 Scope

The discussion for a Continuous Miner (CM) and related Section Level and Operation Level task commands is included in the following Sections 4.4 through 4.6. A summarized task command[8] list is found in Appendix I. Task commands for a shuttle car are included in Appendix II. Some planned commands are listed without detailed description, either because the current equipment does not have such capabilities, or more systematic investigation is needed before these tasks can be defined. In either case, they will be incrementally implemented as longer term project objectives.

4.3 General Syntax

The general syntax is defined as follows to establish the reference systems for the task commands:

* Front Direction: In a local coordinate frame, the forward direction is defined as the positive direction.

* Angle: For all the angular quantities, counter clockwise is defined to be positive; the zero reference is at geographical North in a global coordinate frame, and is at the equipment's or actuator's front direction in the local coordinate frames (Figure 6a).

* Coordinate Frame: A right-handed coordinate convention is used, with the X axis pointing to the right, the Y axis is 90 degrees counter clockwise to the X axis, and the Z axis pointing upwards. Therefore in a global coordinate frame, the Y axis points to geographical North, and in a local frame it points to the equipment's or actuator's front direction (Figure 6a).

* Heading: The angle from North to where the vehicle centerline is pointing, measured counter clockwise (Figure 6a).

* Course: Same definition as the above "Heading" (Figure 6a).

* Bearing: The angle to an object from the centerline of the vehicle (Figure 6a).

* True Bearing: The angle to an object measured from geographical North (Figure 6a).

* Azimuth: The difference in bearing of the centerlines of two objects measured counter clockwise (Figure 6a)[9].

* Elevation: The angle above the horizon or a local reference (Figure 6b).

* Pitch: Angle of the centerline of the vehicle above the horizon (Figure 6b).

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[8]Task Command (TC) is a key word used in the RCS methodology, however, in this paper terms such as 'task', 'command', and 'process' are also used.

[9]There can be different ways to state this definition; this is how the azimuth will be used in this project; for example, the azimuth between the CM and the MCS affects the lasers' efficiency.

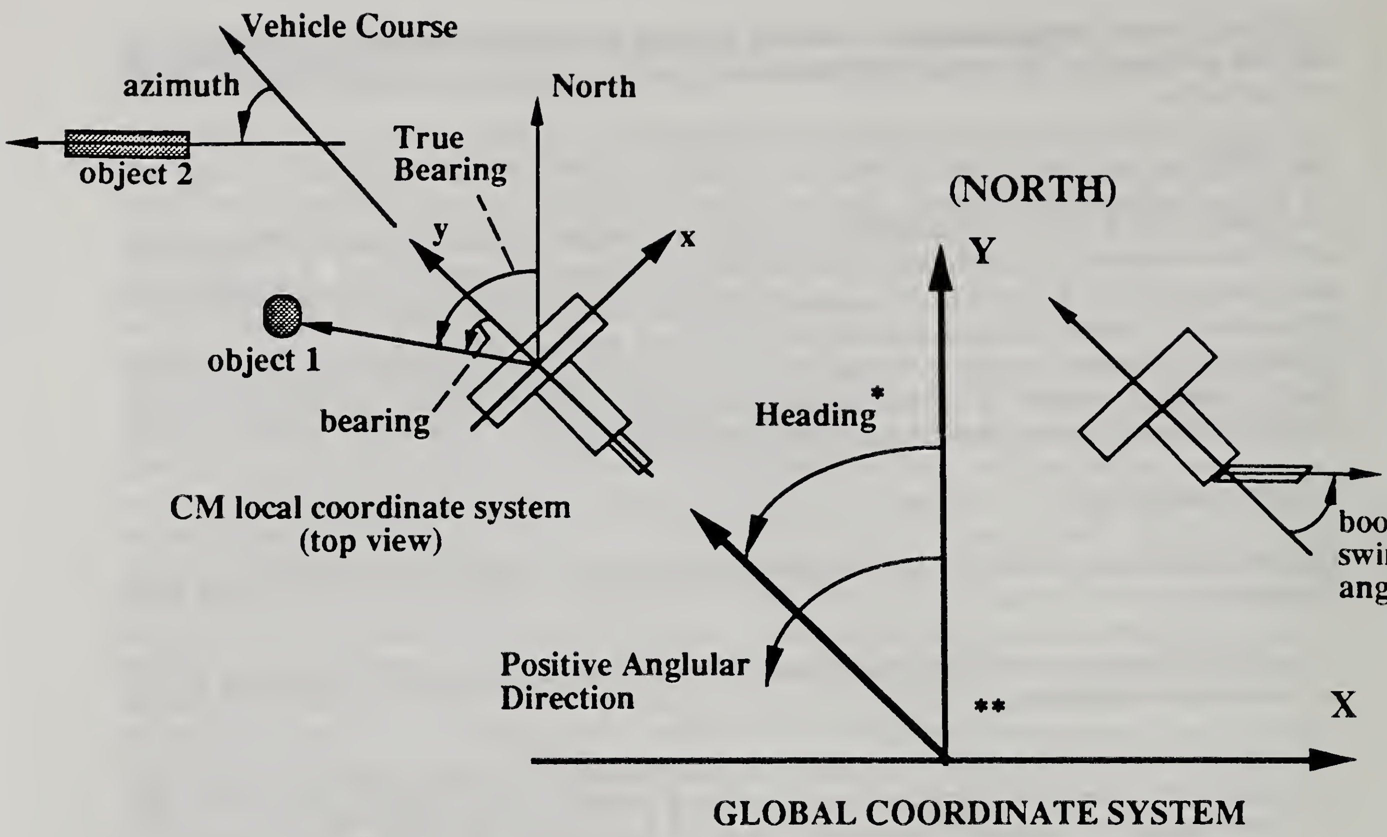

Figure 6a Global and Local Coordinate Systems

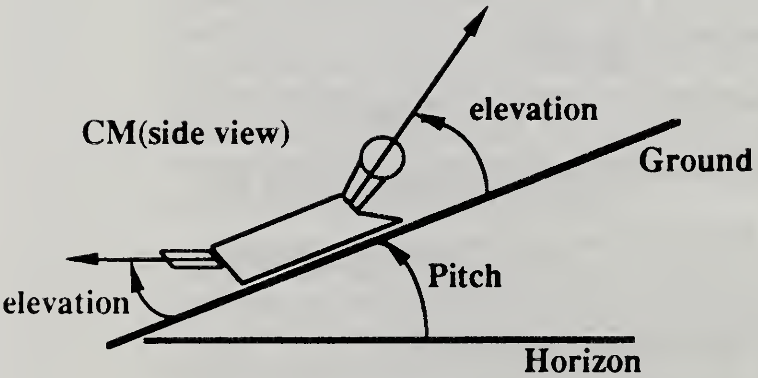

Figure 6b Pitch and Local Elevation Coordinates

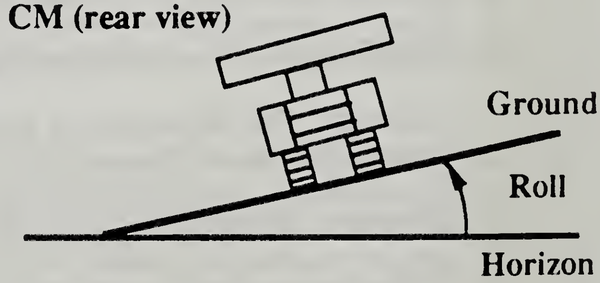

Figure 6c Roll Coordinate

* Labels begin with capital letters imply a reference to the Global Coordinate System
** Z Axis points outwards paper

* Roll: Angle of the X-axis of the vehicle above or below the horizon (Figure 6c).

4.4 Continuous Miner

The Continuous Miner is the primary focus of the Bureau of Mines' Mining Automation effort at this stage, and therefore it is discussed in detail in this paper. The CM receives Equipment Level task commands from the Section Mining Operation subsystem CM Planner, and outputs actuator commands. In the following sections, the BOM interface and the actuator commands are discussed first, followed by the discussions on the higher levels.

4.4.1 The Integration of BOM/NET Commands

BOM has developed a complete set of Continuous Miner primitive functions [Sch 89-2], as well as a set of commands to, and responses from, each sensor package (refer to Figure 3 for the specific sensors). They are all implemented as message packets with a standard format so that they can be sent across the BOM/NET bitbus network to their destinations. The BOM/NET commands are used in this paper in defining the inputs to the Actuator Level for the following reasons:

* To preserve a coherent interface between the RCS and the current BOM automation research work.

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

For these reasons, the BOM/NET CM commands are taken as the Prim Level outputs in an RCS hierarchy. The BOM/NET commands are generally specified for each individual actuator, except for the tramming commands, where one command involves both trams (since this is how CM control switches are wired).

A report describing the mapping of BOM/NET into RCS is in process [Hu 90-2]; an example can also be seen in Appendix III.

4.4.2 Level 1 -- Actuator Level

The output of the Actuator Level TD module contains electrical/hydraulic command signals to each actuator [Jo 82]. The inputs to this Level are the Primitive Level outputs defined for each subsystem, as described in the above Section.

The following Joy CM functions and function categories were derived from the Joy CM 16 service manual [Jo 82] and BOM/NET Specification [Sch 89-2], where complete command names and formats are listed:

* Tramming [Jo 82][10]
    . forward slow / fast
    . reverse slow / fast
    . left turn forward / reverse

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[10]p. 36, Introduction, in the Reference

. right turn forward / reverse
. pivot left / right

* Appendage Hydraulic Motions [Jo 82][11]
  . conveyor up /down, left / right
  . shear up / down
  . drum extension in / out
  . stabilization jack up / down
  . gathering head up /down, extension in / out

* Latching On/Off [Appendix IV]
  . pump motors
  . cutting head motor
  . conveyor
  . main control switch (safety relay)

The World Model support for the Actuator Level TD would include coordinate transformation algorithms and the world map with a proper resolution to support the task decomposition function.

4.4.3 Level 2 -- Primitive Level

As mentioned, the Primitive Level is also referred to as the dynamic control level. It essentially receives task commands which are a series of collision free motion path points between the E-Moves and computes the inertial dynamics to generate smooth trajectory positions, velocities, and accelerations so that efficient equipment and appendage maneuvers can be achieved. In the case of mining equipment, though, most controls are of the on/off type and, therefore the Primitive Level computations are much simplified. Section 4.4.2 specified three categories of commands. For the Tramming and the Appendage commands, the Prim Level controller determines their range, rate, and maximum time (refer to [Sch 89-2] for the standard command format), whereas for the Latching commands, only the actions of 'on' or 'off' are needed.

4.4.3.1 Piloting

The specific important piloting objectives for the CM Prim Level are to

. determine tramming speed
. determine turning method (pivot or one tram halted)
. perform tread slippage control
. determine piloting methods (the reference to follow during piloting)
. test status at intermediate points to see if primitive command objective has been achieved.

There can be different methods for performing piloting in a room and pillar development area. It is assumed here that the center following approach is used, in which the desired wall clearance (proximity) is a predefined quantity. Since the wall surface is generally rough, range information has to 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

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[11] p. 18, Introduction, in the Reference

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 following are the piloting input primitive commands for the continuous mining machine.

* CM_straight (x, y, speed);
  . x, y: the target coordinates for tramming[12];

  . speed: this parameter may have two values: high or low. These values are decomposed to be the proper 'switch positions' in the next lower level, as defined in the CM manual. The drum side is defined to be the forward direction.

* CM_turn (degree_turn_CM, pivot);
  . degree_turn_CM: specifies the relative turning angle in degrees, the direction is as disclosed in Section 4.3;

  . pivot: can be about the center or about either tram; this then can be decomposed into one of the twelve tramming primitives. It is interesting to note that, for example, if degree_turn_CM = -10, then
  'pivot = left' means right tram forward and left tram not moving
  'pivot = right' means left tram reverse and right tram not moving
  'pivot = center' means right tram forward while left tram reverse.

  Note, practically only the lower speed is used during a 'turn' task, therefore the 'speed' does not appear as a parameter in this command.

4.4.3.2 Shearing Control

* drum extension (on/off);
  normally the drum is extended for cutting and collapsed for maneuvering [Jo 82].

* shear (shear_angle);
  . shear_angle: the target drum elevation angle in degrees (refer to Figure 6b for the reference);

  Note that there is a manufacturer-specified drum motor rated current which can be used as a predefined constant for servoing the shearing speed.

* jack (jack direction, inclination);
  . jack direction: can have two values: a value of '0' commands the jack to a retracted position, (it is assumed that the jack always retracts to the original position); while a value of 1 means to push the jack down into contact with the ground according to certain criteria, including inclination.

  . inclination: this parameter is applicable only when lowering the jack. Since it appears difficult for the upper level Planner to compute, in advance, a precise target jack angle, other sensory feedback methods can be suggested. Servo loops such as sensing the CM inclination or sensing the jack hydraulic pressure may be considered. The use of the former technique would be preferred (and is assumed

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[12] Recall that if the specified target position is within the resolution of the current position, then there will be no motion for the CM.

in this paper) because of the availability of the sensors. But the hydraulic pressure will also be assumed to be monitored for the purpose of safety. Several factors stated below have to be taken into account in performing this servo function:

(1) In the hydraulic circuit, a relief valve [Jo 82][13] 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. In TAMME[14] [Schi 88], an I/O channel has been designated to provide this information.

(2) The application of the jack must be completed before the shear operation can start. 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 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.

(3) 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.

4.4.3.3 Conveyor / Gathering Head Control

* gathering head setting (extension, elevation);
  . extension: the desired setting for the CM to gather the cut coal or to navigate;

  . elevation: the desired setting for the CM to gather the cut coal or to navigate.

  Note that the switch function is controlled by the conveyor switch (refer to the E-Move Level corresponding reset command for more detail).

* conveyor setting (latching, swing_angle, elevation_angle);
  This command can be used by two E-Moves, 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.

  . latching: on/off, or forward/reverse, of the conveyor motion;

  . swing_angle: the relative angle from the previous position. Set the boom to the CM center line when performing a subsystem reset, or set it to the middle of the swing angle when performing an alignment for loading.

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[13]p.43 & 45, Hydraulics Section.

[14]Testbed for Autonomous Mining Machine Experiments, an integrated software and hardware system implemented by BOM on the J16 CM.

- . elevation_angle: the target elevation angle (with the reference being at the lowest conveyor position, as seen in Figure 6b), corresponding to the desired conveyor boom height. For the 'coal removal subsystem reset' E-Move task, the target elevation angle would be zero degrees for a navigation reset, and would be the highest position for a cut reset. For 'coal removal subsystem align' E-Move, the target elevation angle would be a fine tuning value relative to the highest position (refer to the E-Move Level discussion). In the higher levels, global coordinates would be used to specify the interface requirement (the height of the conveyor boom) so as to transport the coal from the CM to the haulage unit properly. But in lower level maneuvering, the locally centered elevation angle information is used.

* conveyor boom load (elevation, range);
  - . 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.

4.4.3.4 Dynamic Computations

Referring to the BOM/NET protocol design [Sch 89-2], all message packets which carry the continuous miner primitives (except for latching primitives) have a fixed format, which, besides the command name, contain three parameters: range, rate, and maximum time. These are the primary dynamic considerations for the CM[15].

The latching primitive message packets need no parameter since the 'on' or 'off' states for the subsystems are represented by separate primitives. For example:

#134<cr> means 'conveyor forward' is to be turned 'on', whereas
#135<cr> will turn 'conveyor forward' 'off.'

Hysteresis, a nonlinear dynamic effect which exists in many appendage controls (of bang-bang type), will be taken into account in the Primitive Level dynamics computation. (Refer to BOM research [Schi 88] for more information.)

4.4.3.5 World Model Support

The World Model support for the Primitive Level TD would include dynamic models, filtering algorithms, and the World Map with a proper resolution.

4.4.4 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 defined for each subsystem. They are coordinated 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. Typically the input parameters are defined in a global coordinate

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[15]Moreover, in the TAMME setup, for the tramming functions, the 'range' is to be specified in terms of the length of time for which the motor is on, hence one internal planning function in the Continuous Miner Prim Level will be to convert all tramming distances to commands based on length of time.

system and the corresponding output parameters are defined in the relative (local) coordinate systems[16].

On the E-Move Level outputs, 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 3) 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.

The E-Moves include:

* power up [Appendix IV];
  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 un-recoverable error signals would shut down the machine. This is the first step in starting up the machine.

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

* coal cutting subsystem initialization;
* coal removal subsystem initialization;
* pilot/guidance subsystem initialization;
* main power control subsystem initialization;
* support subsystem initialization;

The following reset commands are executed whenever, during the operation, the appendages are required to be reset.

* coal cutting subsystem reset (switch, drum_extension, drum_angle, jack_position);
  . switch: the cutter motor should be commanded 'off' for the navigation tasks, and 'on' for the extraction tasks.

  . drum_extension: the width of the cutting head; it is precalculated by the planner according to the room and pillar size requirements (but if the drum has only an on/off type of control, then there is no need for this calculation). During navigation the head should be retracted.

  . drum_angle: initial cutting head position;. In a navigation task, the drum is reset to its middle position; in a sump-and-shear operation, the drum is usually reset at the cutting height[17]. The cutting height is normally the coal seam thickness,

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[16]Not always the case, if the relative coordinates turn out to be less convenient to manipulate, then the output may still use a global scale.

[17]In some mining practice, sump from the bottom may alternatively be used (for example, in the Marrowbone Coal Mine Company, WV), for more efficient production.

unless more machine clearances are needed or a loose roof needs to be taken off [Be 87].

. jack_position: for the tramming tasks, this parameter would be used to lift the jack; for the shearing tasks, another 'stabilize' command will be used to position the jack.

* coal removal subsystem reset (switch, conveyor_height, boom_angle, g_head_height, g_head_extension);

  . switch: the parameter to activate or deactivate the conveyor motion (forward, reverse, or off, with the 'forward' defined to be 'away from the cutting drum'). 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. Note that for the Joy CM hardware, turning on the conveyor also turns on the gathering head. Therefore in the software, an additional internal variable 'interlock' may be used for synchronizing the Conveyor and the Gathering Head Prim Level subsystems, and may be used for passing along the status. This is to ensure that the two appendages are set as required, before the coal removal subsystem reset process can be called complete. This variable can have a value of '0' to indicate a 'not synchronized' status and '1' to indicate a 'synchronized' status.

  . conveyor_height: initial absolute height of the boom. The 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' E-Move for exceptions). At this level the unit of 'feet' is used, it will be converted into an actuator angle as an input to the Primitive Level.

  . boom_angle: initial absolute horizontal angle of the boom (Figure 6a), 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.

  . g_head_height and g_head_extension: parameters to position the gathering head to desired height and extension (width of clean-up). For navigation, the gathering head will have to be in its raised position, and for cleaning up coal, it will be kept at a floating (on the floor) position [Be 87].

* piloting/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 may be deactivated.

* main power control subsystem reset;

* support subsystem reset;

Note that all the above steps have to be completed without error before an extraction or a navigation operation can begin.

Another possible way to implement the reset commands is to have a single 'task_type' pointer variable for the commands. This variable may have possible values of 'navigation', 'cutting', or 'idle'. 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_extension = retract;
                drum_angle = default;
                jack_position = lifted          }
```

* navigate to next key pose Z_i;
  Some techniques, such as center following, will be required to perform a navigation task. A 'navigate by following survey marks' may also be used as an intermediate step in approaching complete system automation.

  . Z_i's: a series of key points 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 by the on-board sensor ranges. The cutting head is retracted before navigation starts.

* align to the cutting angle (angle);
  Upon receiving this task command, the planner has to make the following computations:

  (1) Calculate required vehicle heading, depending on whether a cross cut or a straight cut is to be performed; the angle is defined in a global coordinate system, i.e., relative to the coal face, and the lower levels planners will convert it to a CM turning angle.

  (2) Calculate vehicle center position, in order to command the CM to follow the desired cutting pattern.

  This alignment process may be required for each sump (particularly if the CM has tendency to slip off its course). Also, in making a cross cut, a partial cut pattern [An 89] will be used and that would require a continual cutting angle adjustment.

  During the alignment operation, the CM must not lose its position (according to the official mining plan map) and it should not run into local obstacles when performing cutting angle adjustment. (The alignment operation can not count on the preceding navigation command, which created a collision free path for the CM to traverse to the face area; rather, the alignment operation would include different machine maneuvers and has to take into account the possible obstacles in the face area.)

* rotate for heading (angle);
  This command is used to command the CM to turn to a globally defined angle (typically referring to the cutting face), without change of location.

* sump (depth, height);
  . depth: distance for tramming forward; the value should be smaller than a cutting drum diameter and sump speed is limited by the cutting head motor loading.

. height: the initial cutting head position measured from the floor. If its value is zero, the CM is commanded to sump in from the bottom. The height will be converted to an drum angle in this level. Note that usually a cutting subsystem reset command will precede the sump command, hence this parameter may serve only the checking purposes.

Note also that, although the completion of the start up procedure should guarantee that the drum is turning, when a sump is to be performed, it is still a good safety measure to check this precondition. The same is true in the following shear command.

* shear (distance);
  . distance: vertical distance that the drum is to cut, typically the distance between the floor and the local seam height or other selected cutting height.

  Note that an extra predefined constant representing the drum motor rated current will be used to servo shearing speed.

* trim (cutter_position, distance, bearing);
  This command is used for trimming the ridges left on the floor (or the roof depending on where the sump in occurred) due to the shearing geometry.

  . cutter_position: the first action after receiving this command is to position the cutter drum either on the floor or on the roof, depending on where the sump is performed.

  . distance: the desired tramming distance. Coal will be trimmed along the way. The value can either be positive or negative, meaning the CM may have to trim back and forth more than one time.

  . bearing: the target angle relative the the current heading to make the trimming action.

* stabilize;
  Lower the hydraulic stabilization jack to provide a counteracting force during a shearing cycle. The Planner in this level has to compute the stabilization requirements for the Primitive level 'Jack' task 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 the Primitive Level). The Primitive Level controller will then servo according to this derived criteria, either represented as a CM inclination or others, to stabilize the machine. This level's controller would only worry about 'whether the CM is stabilized'

* coal removal subsystem align (height, boom_angle);
  This command is used before the cutting operation (unlike the shuttle cars, in which an 'align to the CM' command will be used through out 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.

- height: the height of the CM conveyor boom for a proper alignment defined in the global frame. Although the Equipment Level Planner computes a nominal target value for it, local ground situation can affect the relative heights among two machines and therefore the target value will be computed on-line.

- boom_angle: 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, as well as a boom elevation pattern according to the haulage capacity, in order to load the cut coal efficiently. 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). On the other hand, 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].

* backward (distance);
This command is similar to the 'navigate to next key pose Z_i' command, except that it is intended for shorter distances or minor position adjustments, and therefore it may not need complete subsystem resets as is needed for the regular navigation tasks.

  - distance: the desired tramming distance. The value can either be positive or negative. An alternative way to specify the target position is to use coordinates, instead of distance.

  Clearance to maintain from the wall is required and it may exist as a predefined constant.

* cable tending;
This may be a required task for an automated machine, but for the present the required actions are assumed to be taken.

The World Model support includes:

- As required by the conveyor loading commands, the world model will include a math model to compute the conveyor swing patterns for the system to achieve the fastest and most evenly distributed haulage loading.
- a world map with proper resolution.
- obstacle avoidance algorithms.

4.4.5 Level 4 -- Equipment Level

The following are the tasks that can be assigned to the continuous miner (CM). Basically the CM can perform several operations: cut coal and load, cut coal, load coal, and navigation.

* start up continuous miner;
  Electrically and hydraulically power the CM up so that it becomes controllable. Refer to Appendix IV for the actual procedure.

* machine test;
  A command used in the initialization period during which all required actions will take place. They include a static shift-start check list as suggested in the J16 CM service manual [Jo 82] (for part wear assessment), and a check list as discussed in the Section Level.

* CM reset (task);
  . task: depending on which plan is to be executed, the CM has to be reset (or initialized) accordingly. The value for the parameter can be 'navigation,' or 'cutting,' etc., as discussed in the E_Move Level.

* alignment to the haulage system;
  After the CM has arrived at the face area, either it already carries the continuous haulage system with it from a previous entry, or the haulage system would approach and align to it. The CM would not tram to approach the haulage system unless the CM's position is unreachable to the haulage system[18].

  The criteria for the alignment may include the machines' center line relative bearing, their clearance at the 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 systems used. If the shuttle cars are used, then the coordination strategy would be defined as:

  . 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. This completes the 'alignment to the haulage system' task.

  . 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' (or the alike) 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.

  On the other hand, if a continuous haulage system is used, the coordination strategy would be defined as:

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[18]This task is assumed to be performed before the CM aligns to the cutting angle, because (a) It is easier for the haulage system to align to the CM than for the CM to align to the haulage system. (b) The 'align to the cutting angle' command would be a continual process required for each sump, particularly when the CM is following the cross cut pattern (see the align command for more detail).

. prior to cut: The continuous haulage system would physically engage with the CM. The CM will then position the boom to complete the 'alignment to the haulage system' task (sensors may be needed to accomplish this).

. during the cut: The CM 'coal load' E-Move will swing the boom and load the coal. Fault conditions may occur in the continuous haulage system: the system may become jammed, it may be stretched to its limit, it may scratch the edges of corners as it turns, etc.. Under these situations the required action for the continuous haulage system is to send a 'pause' signal to the CM.

* cut_load_pause (cut distance, pause, cutting angle);

  . cutting distance: 'Cut' is used by some mining people to define the cutting depth. However, it is used in different ways. One definition in the mining dictionary [Mi 68] states "cut under the coal to a depth of five feet and for a width of fifteen feet"; other people (such as Marrowbone coal mining people) use it to mean cutting for a depth of twenty feet. From an automation point of view, there may be a real-time computed variable cutting depth based on different conditions such as local coal seam formation or timing constraints (for example, if the current shift is scheduled to end in another 45 minutes), then the desired cutting distance must be computed accordingly. Therefore only a symbolic name will be specified.

  Recall that when a change in the operation conditions dictates, replanning may be needed to accommodate the change. Either a new cutting distance needs to be computed so that the task can be accomplished in time, or an interrupt will be generated to suspend the task when necessary.

  . pause: if the shuttle cars are used to transport the coal, generally several car loads are needed for a cut. When 'pause' has a value of '1,' the haulage system is not available, as discussed in the 'alignment to the haulage system' task. The CM has two options under this situation, wait and do nothing, or cut without loading to a maximum allowed amount and load when the haulage system 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 system through the world model control hierarchy.

  . cutting angle: the cutting approach angle relative to the coal face; 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.

  The first action taken upon executing the 'cut_load_pause' command is to reset all E-Move level subsystems (such that the drum is at the desired extension and height). The alignment of the haulage system is then checked. After these are all completed, the CM starts to perform a series of 'align to cut - sump - shear & coal load - trim & coal load' cycles. The same procedure applies also to the next two similar commands.

* cut_no_load_pause (pause);

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

* clean_up_pause (pause);
  This command can be (but not necessarily) 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 sweep 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 (or start cutting; this may result in totally asynchronous cutting and loading actions which may not be desired).

* navigate (Z);
  . Z: destination; a global position in the mine where the next operation will take place.

  The first action taken upon executing the command is to check appendages' positions. Requests for reset, such as whether the drum is collapsed, whether the conveyor motor is stopped, or whether the boom position is correct, will be made, if necessary, before the tramming function is performed.

* back in/out (location);
  This command is similar to the 'navigate (Z)' command, except that the command will typically be used for shorter distances or position adjustments (one typical example is to back out after completing one side of a twenty foot cut; refer also to the 'align to the haulage' command for a possible usage of this command); therefore the CM may not need a complete 'CM reset' as it does for the regular navigation tasks.

  . location: destination for the CM. The determination of this new position should take into account what the next plan is, if possible.

  Clearance to maintain from the wall is required and which may exist as predefined constants.

* CM shut down [Jo 82][19];
  There are seven shut down devices installed on the Joy 16 CM[20] mining machine (circuit breakers, main switch, emergency switch, and panic bar), any of which can be switched to activate a shut down.

* cutting bit maintenance;
  A currently non-existent capability, required actions are assumed to be taken.

The World Model support would include a world map with a proper resolution.

4.4.6 Level 5 -- Section Control Level

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

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[19]p. 14, Introduction Section.
[20]As mentioned in the Introduction, Joy 14 CM may have slightly different features for a shut down operation. This has to be addressed in the future.

Commands include:

* section initialization;
  This task is applicable only when a new section or a new mining plan is started; afterwards, a 'shift start initialization' task will be used.

  The work in this task includes:
  . count the required resources designated by the upper levels;

  . derive the starting locations for the equipment from the designated mining area, 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.

* 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 and subsequent adjustments, to be performed. Consequently, the changed state variables have to return to 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 system:

  . A feedback test procedure that compares the test commands and the sensory feedback to test the readiness of each piece of equipment. Some of the I/O channels on the TAMME 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 can be designed using the on-line machine operation data to provide long-term machine health trend prediction.

  . An expert system being implemented by BOM [Mich 89] can be used to diagnose the CM's electrical system, mechanical system, or hydraulic system problems.

  . A machine start up sequence (Appendix IV).

  . A static check list suggested by the Joy Company [Jo 82].

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

  More comprehensive initialization procedures can be designed. But 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 will come up with a mining plan and send down a decomposed cutting sequence.

  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 will be discussed in the World Model design; in such a design both the computation efficiency and current convention will be taken into account.

* emergency shut down [Jo 82];
  This command is activated in response to equipment health, human safety or an 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;
  Necessary equipment relocation for purposes such as maintenance, replacement, safety backout, etc..

The World Model support for the Section Level Task Decomposition (TD) module 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 with a proper resolution.

4.4.7 Level 6 -- Production Control Level

The following commands are the inputs to the Production Control Level that are related to the discussion of the previous lower levels commands:

* virtual cell formation (production goal);
  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 Level controller. Each equipment can be identified by a predefined BOM/NET node number.

* production operation (goal, method);
  . goal: the production goal for the i'th extraction operation subsystem, in terms of tonnage;

  . method: the mining method, such as room & pillar, long wall, etc..

5. State Transition Diagrams for Plan Description

The methodology of state transition diagrams and how they are applied in an RCS architecture to represent plans is described below. A series of examples illustrating a vertical swath of task decomposition are also explained.

5.1 Methodology

State transition diagrams (STD) are used in task decomposition, in plan description, and in 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. In the E-Move Level, the Piloting/Guidance (P/G) subsystem can not enter the 'align_to_cut' state until all other subsystems complete their reset activities successfully. 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' when a corresponding 'command' is being executed, and the corresponding 'activity' is being exhibited. Exceptions can be seen for some states such as 'done', where the corresponding 'command' and 'activity' are trivial. 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 (Figure 7), a bubble with an enclosed name is used to represent a system's state (and the implied command), and the arrowed edges entering or leaving a bubble are used to describe the system's state transitions. Together the bubbles and edges completely describe how the system is to enter, to stay, and to 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 state values, special flags, predicate function values, or other system's status combined by "and's"[21] and/or "or's".

A command list such as those in Section 4 is required to identify all possible activities that the system is able to perform.

One general assumption in state transition diagrams is that each command has a timeout limit. If the command can not be accomplished within the time limit, then the system automatically branches out to a 'suspend' state, meanwhile, fault reports are issued and proper actions need to be taken either by human action or by certain emergency recovery processes such as the Executor emergency planning routines.

5.2 An RCS Plan

An RCS plan can be described by one or a series of STD's. The TD module for any subsystems has a Planner (PL) for each of its next lower level subsystem (or actuator) that it controls. This Planner generates (or selects) a plan for the subsystem (or actuator) that it controls. The commands in the plan are passed down sequentially by the Executor (EX) associated with the PL to the Job Assignment Module (JA) of the next lower Task Decomposition (TD) module (or to the actuator).

Each plan begins with a 'start' state and ends with a 'done' state. All the state transitions are subject to 'time-out' checks, they are also subject to interrupts (generated by either human or computer) that suspend certain commands and send the system into the next states.

5.3 Plan Frame

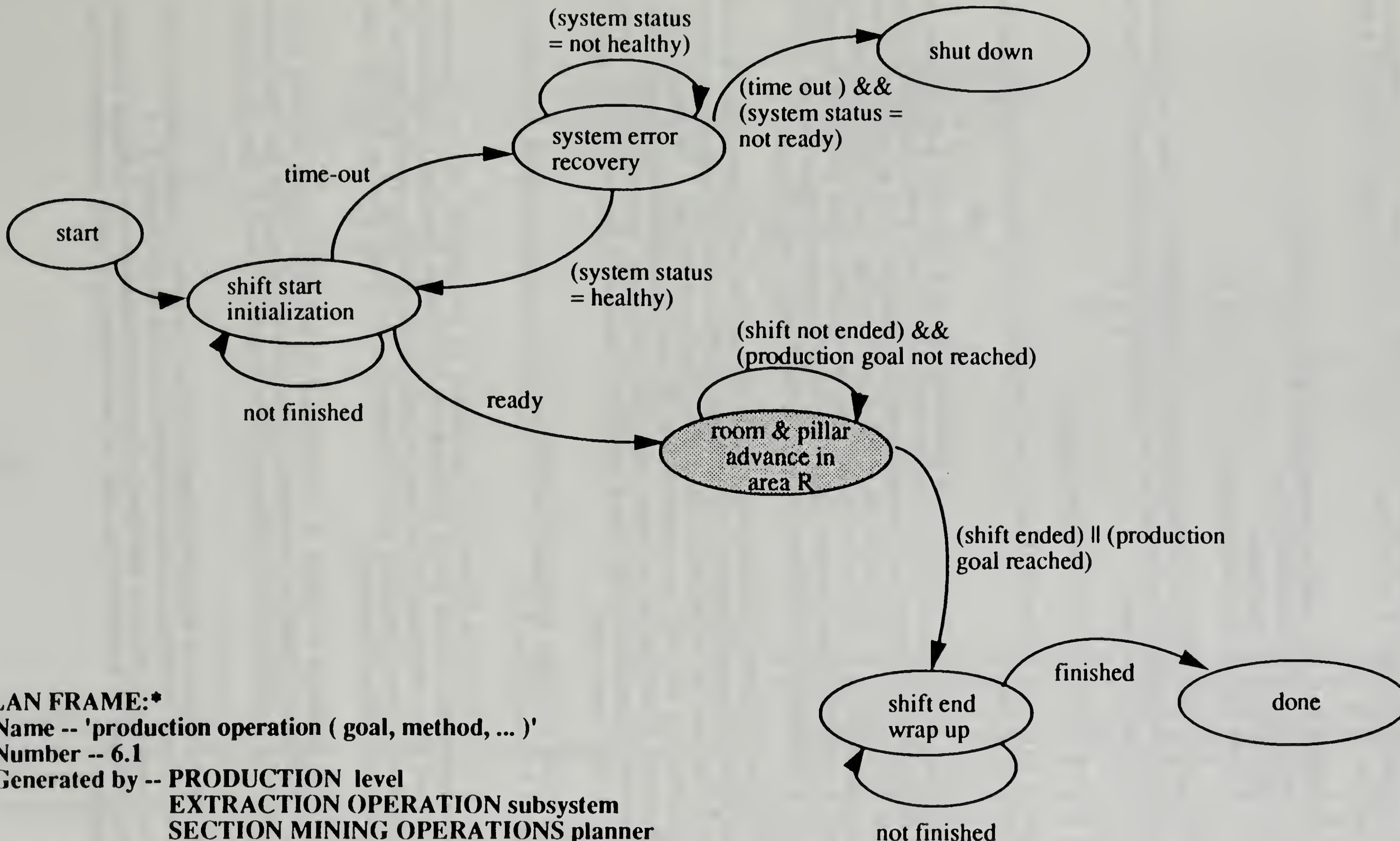
Each state transition diagram uses a plan frame which includes the following slots to identify the plan:

* Plan Name -- The name of the command to be described by the current state transition diagram is used as the name for this plan.

---

[21] Some theories suggest that no "and's" would be used because the STD technique does not have the capability of keeping history. But this can be considered as an implementation issue, meaning an external 'and' operation will be used to generate the combined signal, therefore "and's" are still used in this paper to express the actual transition requirements.

PRODUCTION OPERATION PLAN



PLAN FRAME:*
Name -- 'production operation (goal, method, ...)'
Number -- 6.1
Generated by -- PRODUCTION level
EXTRACTION OPERATION subsystem
SECTION MINING OPERATIONS planner
Decomposition -- plan 5.1 for the task 'room & pillar advance in area R'
Date -- 12/29/89

* This is a simplified Production Level plan with a purpose to highlight the state "room & pillar advance in area R"

All state transitions in all diagrams are subject to timeout checks as well as external interrupts.

Figure 7 A Production Operation 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[22].

* 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[23] describing each of these commands.

5.4 A Vertical Swath of State Transition Diagrams

A series of STD's, in hierarchical order, are developed to illustrate the successive task decomposition process:

* Plan 6.1, as shown in Figure 7, is generated by the Production Level Extraction Operation #i subsystem Planner. The first step of this plan is a shift start initialization. Detected inconsistencies such as equipment non-readiness will 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 all together 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 Operation in Area R', the criteria to end this task are that either a shift has come to an end, or the production goal has been met. Afterwards a 'Shift End Wrap Up' task will be executed before the plan is completed and the next plan is generated. Note that in the room and pillar command, 'area R', with a coarser resolution, is specified, rather than a particular location with finer resolution, which is used in the lower levels.

  The 'Room and Pillar Advance in area R' command is decomposed into the following Plan 5.1 through Plan 5.3.

* Plan 5.1, as shown in Figure 8, is generated by the Section Mining Operations subsystem of the Section Level. After the Job Assignment Module (JA) receives the room and pillar command, it performs a spatial decomposition to assign tasks to the relevant subsystems, including the CM planner and the Bolter Planner, and then waits for the status report from them.

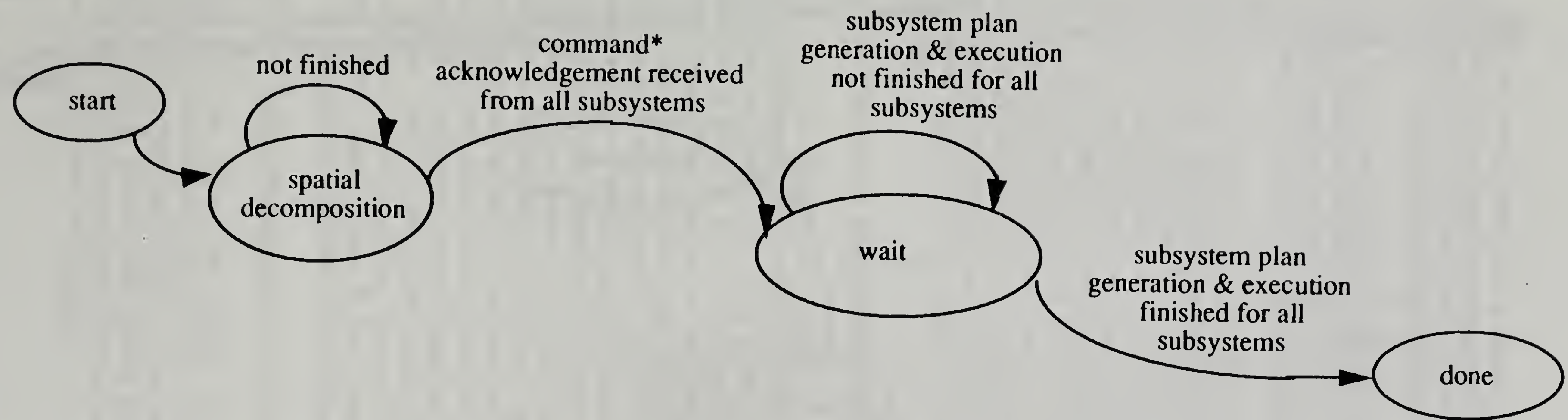
* Plan 5.2, as shown in Figure 9, is generated by the CM Planner residing in the Section Mining Operation subsystem of the Section Level. The Job Assignment Module (JA) assigns the CM a room and pillar operation in area R. The CM plan that

---

[22]Later on if the complexity of the system increases, there may be a need to assign a number for each Planner in the Level and use them as an additional segment in defining the Plan Number.

[23]Except for the lowest level diagrams, each bubble will have a decomposed sub-level diagram to describe itself. However, during the development stage, only the shaded bubbles are further decomposed into their sub-level diagrams.

ROOM & PILLAR ADVANCE JOB ASSIGNMENT ACTIVITY***



PLAN FRAME:
Name -- room & pillar advance in area #R job assignment **
Number -- 5.1
Generated by -- SECTION level
SECTION MINING OPERATION subsystem
JOB ASSIGNMENT module
Decomposition --plans 5.2 & 5.3
Date -- 12/29/89

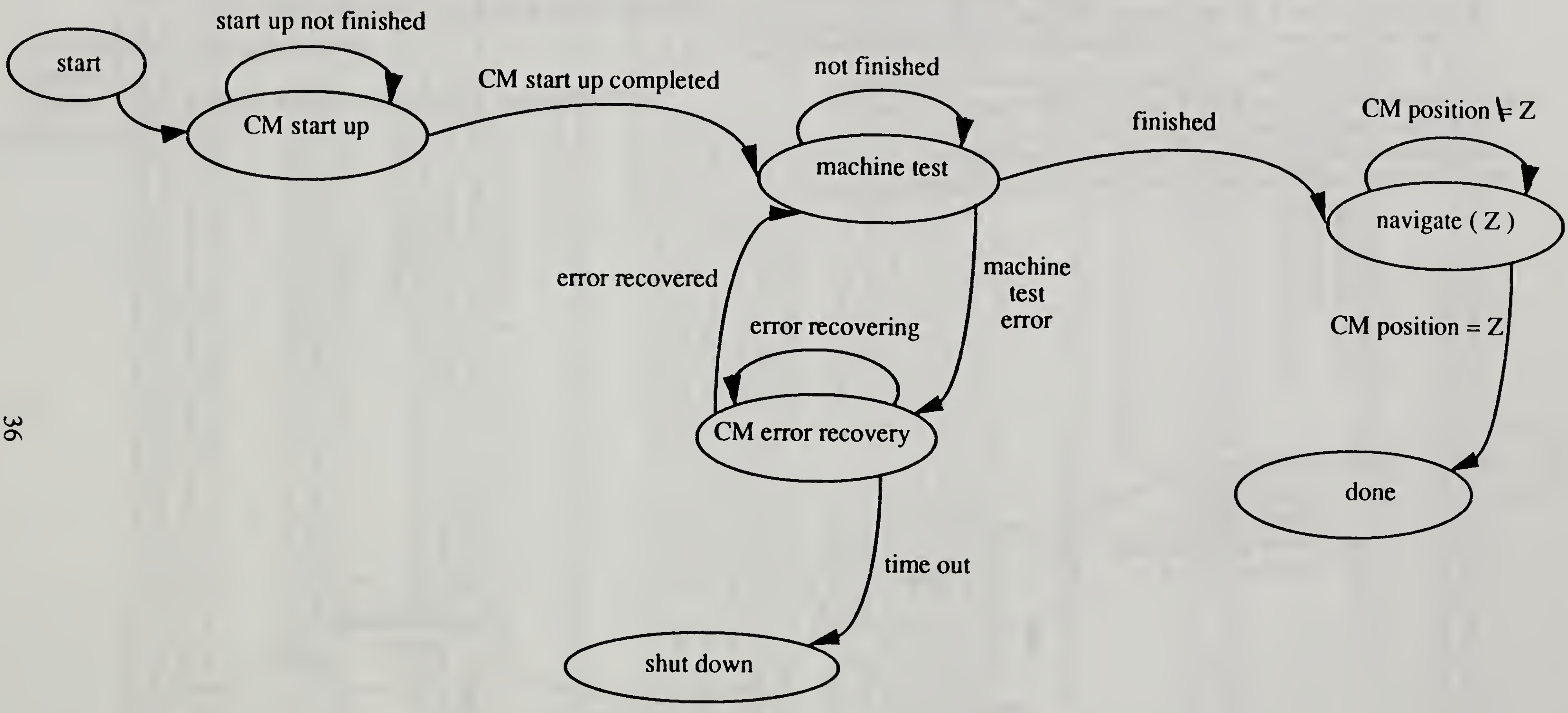
* Each transition condition contains a required status data list; in this particular case, the state transition requirements can be defined as:
(CM room & pillar advance in area#R command received) &&
(Haulage system support CM #1 in area #R command received) &&
(Bolter bolting request in area #R command received)

** Command name not implemented in Task Command List yet.

*** This 'plan' is not the same as others, since it is not generated by a planner, but rather is used to describe the job assignment activity.

Figure 8 A Room & Pillar Advance Job Assignment Plan

ROOM & PILLAR ADVANCE NAVIGATION PLAN



PLAN FRAME:
Name -- CM room & pillar advance in area #R navigation *
Number -- 5.2; to perform the 'test and navigation' subtask for the referenced command
Generated by -- SECTION level
SECTION MINING OPERATION subsystem
CM planner
Decomposition -- plan 4.2 for the task 'navigate (Z)'
Date -- 12/29/89

* command name not implemented in Task Command List yet

Figure 9 A Room & Pillar Advance Navigation Plan

is selected would start 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).

* Plan 5.3, as shown in Figure 10, is also generated by the CM Planner residing in the Section Mining Operation subsystem of the Section Level. At the beginning of this plan, the machine is expected to be at some desired location, otherwise a time-out signal would be issued and Plan 5.2 would be selected and executed first.

  The CM can perform several different operations: cut and load coal, cut (without loading coal), load (without cutting) the loose coal (clean-up operation), and do nothing (wait). This Plan 5.3 describes a cut and load operation. 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, the haulage unit is away, is full, is jammed, or has other problems. The conditions for the CM to exit the cut state are either the cutting distance is reached (refer to Section 4.4.5 'cut_load_pause' command definition for the possible replanning of the desired cutting distance) 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.

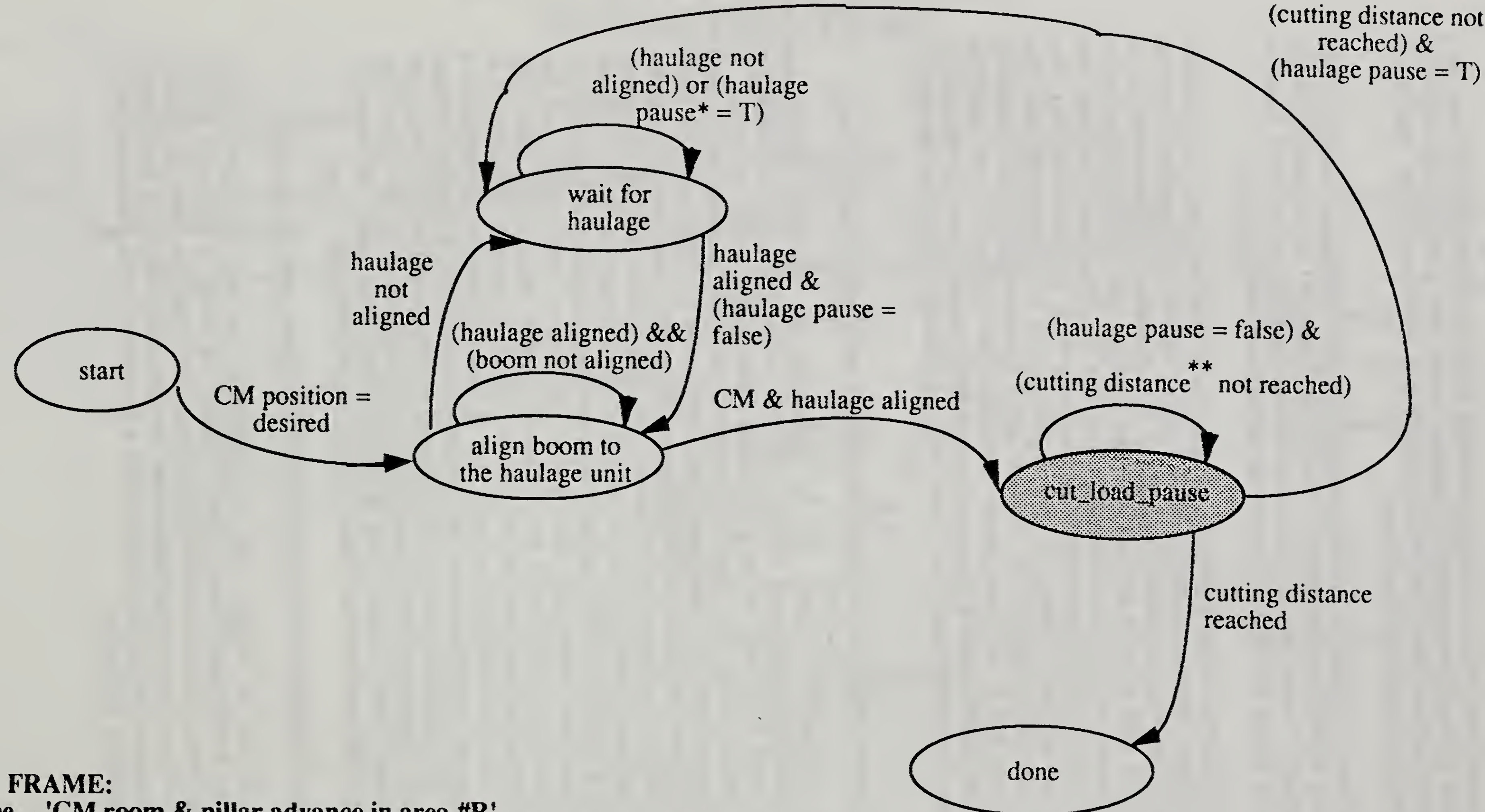
  The 'cut_load_pause' task is decomposed into the following next lower level plan.

* Plan 4.1, as shown in Figure 11, is generated by the CM equipment Piloting/Guidance (P/G) subsystem Planner. The P/G subsystem is reset according to the types of tasks that need to be performed ('navigation', 'cut' or 'wait', as described in Section 4.4.4). The plan includes a wait in order to synchronize other parallel tasks. For example, the stabilization jack needs to be in a lifted position. After all the CM subsystems are reset, the P/G planner issue a tram command to align the machine to a desired cutting angle. A sump task will follow. During the sump, several situations may happen that would lead to an exit of the state: first of all, on-line Coal Interface Detection (CID) devices may discover an unexpected layer of rock. The Piloting/Guidance subsystem then has to go into a 'wait' state, and the emergency replanning activity will take place to decide what to do next. The replanning may result in a request for the P/G subsystem to resume the sump, or it may simply ask the P/G subsystem to back out. A second situation to terminate a sump is that either the sump distance or the cut distance is reached. If a sump distance is finished, the P/G subsystem would typically wait for the Coal Cutting subsystem to perform a 'shear' operation, then proceed for a trim operation to cut the ridge. The 'align to cut - sump - shear & load - trim & load' cycles (performed by different E-Move subsystems) are continued until the cutting distance is reached.

  The 'sump' task is decomposed into the next lower level plans, one of which is:

* Plan 3.1, as shown in Figure 12, is generated by the E-Move Level Piloting/Guidance subsystem Tram Control Planner. A sump is basically a CM tramming forward task, with the cutter motor and the Coal Interface Detection (CID) devices running. Wet or loose ground may cause the CM to slip, which in turn causes the CM_straight distance not to be reached within a given time limit. The system may need to be shut down at this point.

ROOM & PILLAR ADVANCE PLAN



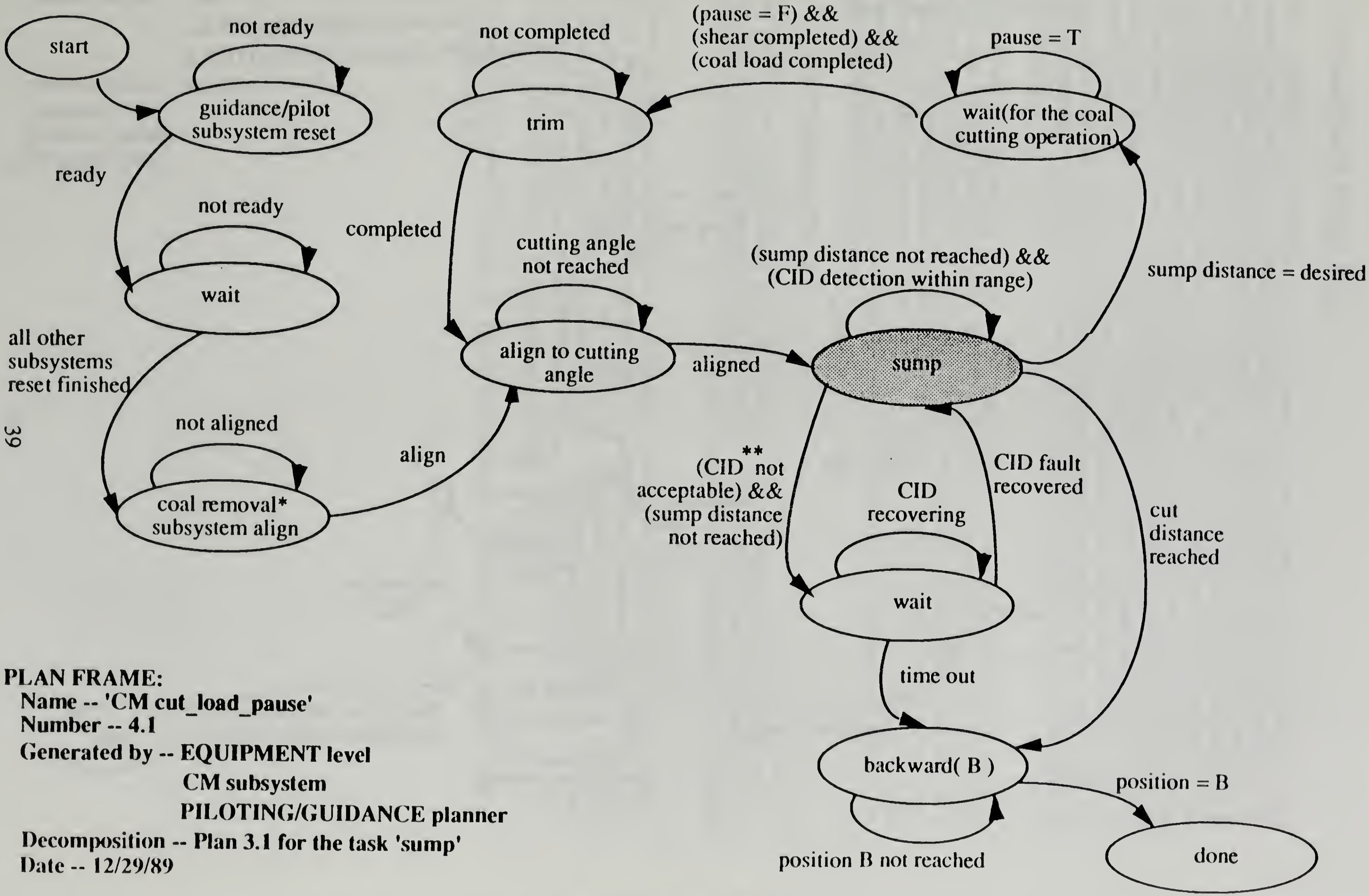
PLAN FRAME:
Name -- 'CM room & pillar advance in area #R'
Number -- 5.3
Generated by -- SECTION level
SECTION MINING OPERATION subsystem
CM planner
Decomposition -- Plan 4.1 for the task 'cut_load_pause'
Description -- to perform the cutting operation, typically after the execution of Plan 5.1 assures the CM's position at the face.
Date -- 12/29/89

* The 'pause' usually indicates that the haulage system is full, out of place, jammed, or other problems. In any case, the CM can 'wait' as this plan shows, or perform other activities as the following plans show.

** It can be 20 or 40 feet, or other distance as specified.

Figure 10 A Room & Pillar Advance Plan

CUT_LOAD_PAUSE PLAN

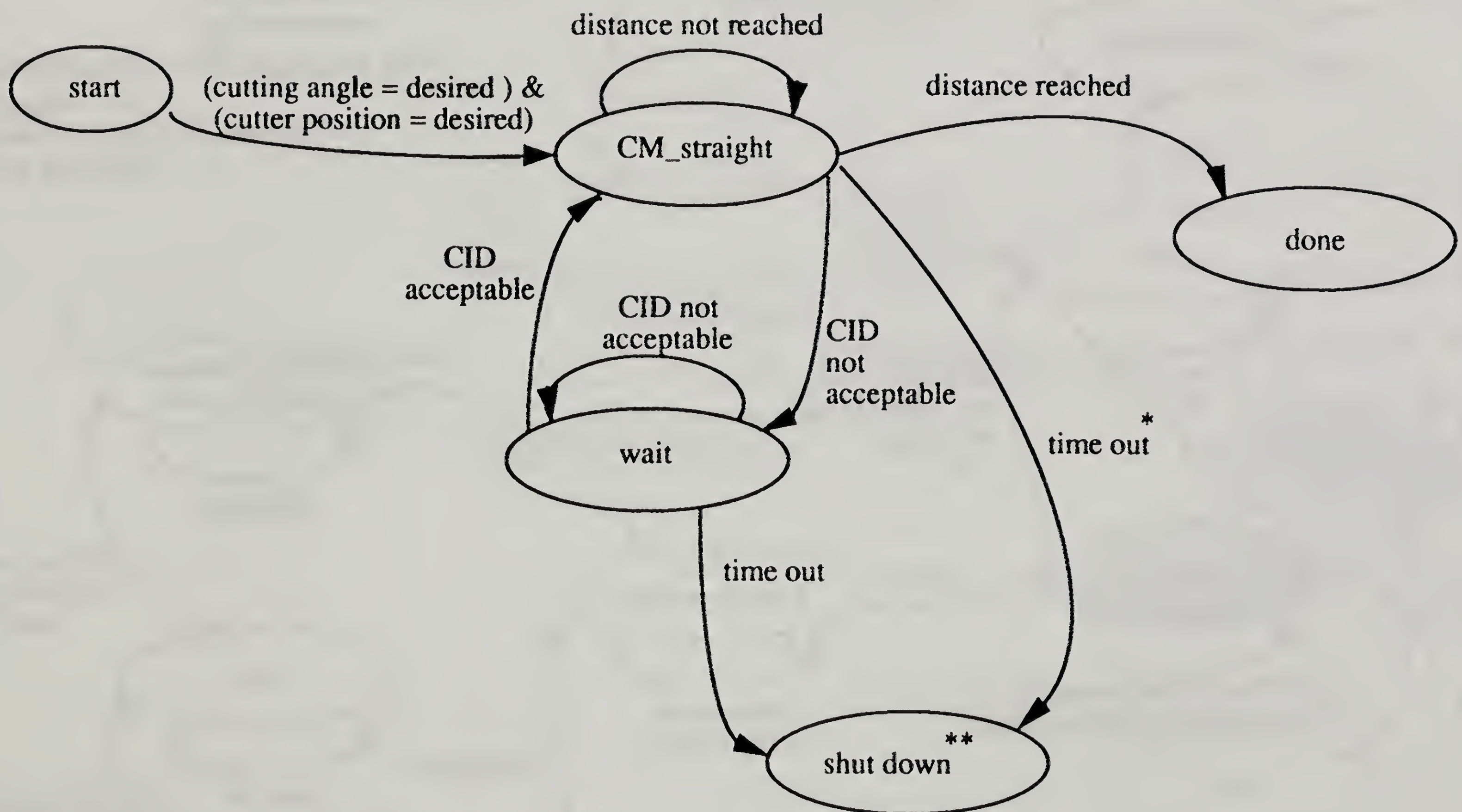


PLAN FRAME:
Name -- 'CM cut_load_pause'
Number -- 4.1
Generated by -- EQUIPMENT level
CM subsystem
PILOTING/GUIDANCE planner
Decomposition -- Plan 3.1 for the task 'sump'
Date -- 12/29/89

Figure 11 A Cut_Load_Pause Plan

* mostly for checking purpose (see Plan 5.3)
** Coal Interface Detection

SUMP PLAN



PLAN FRAME:
Name -- 'sump'
Number -- 3.1
Generated by -- E-MOVE level
PILOTING/GUIDANCE subsystem
TRAM CONTROL planner
Decomposition -- Plan 2.1 for 'CM_straight'
Date -- 12/29/89

* Can be due to tread slippage.
** EX emergency planning takes place.

Figure 12 A Sump Plan

6. Summary and Future Work

The automation of a continuous mining machine and related equipment based on the hierarchical real-time control task decomposition methodology was described. In developing the system's functional hierarchy, a guideline involving software modularity and subsystem autonomy, the system's operation, the environment, the computing technology (both hardware and software), etc., were discussed. The guideline also establishes the functional requirements for each subsystem and each level. In performing the task analysis and defining the system's activities, the system's pre-existing capability is taken into account, the machine coordination strategy has to be decided, and a transformation of coordinate frames and resolutions has to be observed during the hierarchical task decomposition. State transition diagrams are used to define plans using the task commands (including constraints) developed using the RCS task decomposition methodology.

By following these steps, a system's capability, behavior and interaction with the external world can be described. This is the first stage of the task decomposition methodology. An abstract high level goal for the system can then be logically decomposed, planned, and executed by the required equipment. The next stage of work includes designing software algorithms and requirements for the Job Assignment Modules, the Planners and the Executors to select and execute these activities, and the world model modules to support the task decomposition requirements.

7. Acknowledgements

The paper is an application of RCS methodology. RCS methodology was originated by, and is evolving under, the leadership of Dr. Jim Albus, Chief, Robot Systems Division, NIST. I acknowledge Dr. Albus' comments and in particular, his permission to use Figure 1.

I also extend my appreciation to Dr. Christopher Jobes, Dr. George Schnakenberg and the rest of the engineering staff involved, at the United States Bureau of Mines, Pittsburgh Research Center, as well as Mr. John Horst, Mr. Don Orser, and Mr. Richard Quintero, of the Robot Systems Division, National Institute of Standard and Technology, for their comments and suggestions. Also, Mr. Maris Juberts, who was with NIST and is now with NASA, for his early work on the functional hierarchy (Figure 2).

My thanks to Cheryl Hutchins of the Robot Systems Division, NIST, for her careful editing of this paper.

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Appendix I

Task Command List

4.[24] Continuous Miner

4.3.1 Actuator Level Inputs
Refer to BOM/NET Specifications [Sch -2]

4.3.2 Primitive Level Inputs
4.3.2.1 Piloting
* CM_turn (degree_turn_CM, pivot);
* CM_straight (x, y, speed);
4.3.2.2 Shearing Control
* drum extension (on/off);
* shear (shear_angle);
* jack (jack direction, inclination);
4.3.2.3 Conveyor / Gathering Head Control
* gathering head setting (extension, elevation);
* conveyor setting (latching, swing_angle, elevation_angle);
* conveyor boom load (elevation, range);

4.3.3 E-move Level Inputs
* power up;
* coal cutting subsystem initialization;
* coal removal subsystem initialization;
* pilot/guidance subsystem initialization;
* main power control subsystem initialization;
* support subsystem initialization;
* coal cutting subsystem reset (switch, drum_extension, drum_angle, jack_position);
* coal removal subsystem reset (switch, conveyor_height, conveyor_swing, g_head_height, g_head_extension);
* piloting/guidance subsystem reset;
* main power control subsystem reset;
* support subsystem reset;
* navigate to next key pose Z_i;
* align to the cutting angle (angle);
* rotation for heading (angle);
* sump (depth, height);
* shear (distance);
* trim (cutter_position, distance, bearing);
* stabilize;
* coal load;
* backward (distance);
* cable_tending;

4.3.4 Equipment Level Inputs
* start up continuous miner;
* machine test;
* CM reset (task);

---

[24]The numbers refer to the sections that describe the corresponding commands.

* align to the haulage system;
* cut_load_pause (pause, cutting angle);
* cut_no_load_pause (pause);
* clean_up_pause (pause);
* navigate (Z);
* back in/out (location);
* CM shut down;
* cutting bit maintenance;

4.3.5 Section Control Level Inputs
* section initialization;
* shift start initialization;
* shift end wrap-up;
* room and pillar advance in area #R;
* emergency shut down [Jo 82];
* equipment relocation;

4.3.6 Production Control Level Inputs
* virtual cell formation (production goal);
* production operation (goal, method);

A.II Shuttle Car [Appendix II]

A.II.1 Actuator Level
steer (target);
tram (direction_shuttle, speed level);
brake;
brake_emergency;
conveyor_shuttle (direction, level);

A.II.2 Primitive Level
shuttle_turn (degree_turn);
shuttle_straight (distance, speed);
shuttle_change_speed (change);
conveyor_on (control, direction);

A.II.3 E-Move Level
shuttle power up;
shuttle orient (degrees);
shuttle navigate (Zi);
shuttle wait (time);
shuttle load;
shuttle unload;

A.II.4 Equipment Level
start up shuttle car;
machine test;
align to continuous miner;
load;
shuttle car navigate (Z);
align to feeder;
unload;
exchange;
shuttle car shut down;

backout (B);
shuttle car shut down;

Appendix II
The Shuttle Car Control and Its Task Command List

1. Operator Control of Joy 10SC22 Series Shuttle Car [Jo 81]

1.1 tram control

. speed selection: slow, fast, off

. tramming operation: two steps are required, select speed and push tram pedal

. direction: the shuttle cars are designed to operate in dual directions. In the two seat models, there are two sets of tram pedals, seat directions are consistent with tram directions, whereas in the one seat models there is a directional switch.

1.2 steer

There is only one steering wheel, hence if the operator sits facing the discharge end, then the clockwise (CW) steering makes the shuttle turn right, but if he sits facing the loading end, CW steering will turn the shuttle left.

1.3 conveyor control

There are three types of inputs: on / off, raise / lower, and forward / reverse; in which lowering the conveyor also releases the shuttle parking brake[25]; this fact together with the fact that the shuttle usually has to tram to have itself filled up indicates that the only occasion the shuttle raises the conveyor is when the shuttle does not need to be in motion.

There can be two speed selections for conveyor forward in some models, but this is ignored in our work for simplicity.

1.4 brake

Two separate inputs can set the brake; (1) service brake operated from the pedal during normal operation; (2) emergency / park brake operated from a panic bar (or by raising the conveyor).

1.5 cable reel control

Based on the force balance between the system's hydraulic pressure and the cable tension. Usually this is preset and does not require operator I/O.

1.6 Other things such as fire suppression will be considered only by setting up dummy commands.

2. Shuttle Car Task Commands

2.1 Actuator Level

2.1.1 Piloting

steer (target); steer has continuous control, where

target: relative steering angle, a positive value indicating a clockwise (CW) direction and a negative value corresponding to a counterclockwise (CCW) direction in the alignment operation. The steering angle and direction will be computed from CM-shuttle range differentials.

---

[25]Parking brake is a spring loaded device. Lowering the conveyor closes the hydraulic valve, pressurizes the system, and releases the brake by untying the spring.

For all servo actions in the system, tolerances (servo errors) can be dealt with by two methods, (i) dynamically specified, (ii) predeclared as constants. The latter will be used for now; currently there is no intention to output the actual servo errors.

tram (direction_shuttle, speed level);
    direction_shuttle: either loading direction or feeding direction.
        speed level: may have 3 speed levels—high, low, idle.

Note that the above two commands can be executed concurrently.

brake; executed during normal operation from the service brake mechanism (there is a brake pedal for manual activation).

brake_emergency; executed when parking or at emergencies from the emergency brake mechanism (there is a panic bar for manual activation).

2.1.2 Conveyor

conveyor_shuttle (direction, level);
    direction: 3 stage control: forward / reverse / off; note that during normal operation the conveyor is usually not commanded to be 'off'; note also that turning on the conveyor also turns on the gathering head.
    level: high or low, a high conveyor level will trigger the tram emergency brake.

2.2 Primitive Level

shuttle_turn (degrees); where
    degrees: specifies the relative turning angle in degrees, a positive angle denoting a clockwise direction (from above the machine), and a negative angle indicating a counterclockwise direction;

shuttle_straight (x, y, speed); where
. x, y: the target coordinates for tramming;
. speed: the speed for the shuttle car.

shuttle_change_speed (change);
    'change = 1' means increase the tramming speed by one notch (in an order of high reverse, low reverse, idle, low forward, and high forward). For example, the speed will change to idle if the shuttle car is running at low speed reverse. Note that if the current speed is '+2,' the 'change = 1' assignment will not change the speed and a warning signal will be issued.
    'change = 0' means keep the current speed.
    'change = -1' means decrease the tramming speed by one notch. Note that if the speed is currently '-2', a 'change = -1' will not change the speed and will trigger a warning signal.
    Note also that the parameter 'change' can have only these three values.

Although the shuttle car is assumed to have only a limited number of sensors, it is assumed that there will be enough sensor data to allow the shuttle car to perform piloting functions using a center following strategy.

conveyor_on (control, direction);
    control: a value of '1' means turn on the conveyor, '0' means turn it off.

direction: when the conveyor is on, its direction can be either 'forward' or 'reverse,' where 'forward' is toward the feeding end.

2.3 E-Move Level

Shuttle cars can either be equipped with a complete set of sensors so as to be able to perform very intelligent navigation and piloting, or they can have only a limited number of sensors, and then the majority of shuttle car operations would be in a script mode. For example, in the shuttle car alignment operation, a script could navigate the shuttle car through the prespecified routes with limited help from short range proximity sensors to sense the proximity of the wall and any objects in the front of the shuttle car before it comes within range of the CM's ranging sensors. On the other hand the shuttle car can also be equipped so that it can intelligently approach targets from long distances away (optimizing routes, avoiding obstacles, etc.).

We will assume that the continuous miner is the 'master' and contains most of the intelligence in the system. With this assumption the shuttle cars would be operated in a scripted reaction mode for most operations.

The task commands in this level can include:

shuttle power up;
Start up the machine.

shuttle orient (degrees);
degrees: relative turning angle; note that for a car with wheels the request for orientation does not always equate to a steering angle, the car must maneuver itself so that its heading points in the intended direction; this is different from equipment like a CM with tramming locomotion.

shuttle navigate (Z_i);
Z_i: the key poses which route the shuttle car to its destination, note that navigation may not always be in straight lines, therefore it may be necessary to include steering in the decomposition of subtasks.

shuttle wait (time); an empty car is to wait at the change point until the loaded one changes out.

shuttle load;

shuttle unload;

2.4 Equipment Level

. start up shuttle car;
Electrically and hydraulically power the shuttle car up so that it becomes controllable.

. machine test;
a command used in the initialization period during which we assume all required actions will take place, these include a static shift-start check list (basically for part wear assessment), and a dynamic check list as discussed in the Section Level.

. shuttle car navigate (Z);

Z: end point; typically an end point is the CM site, feeder site, change point or backout point; wall proximities are assumed predeclared so that they may not appear as arguments in the command.

. align to continuous miner; refer to Appendix 2 for alignment definition, all variables values are predeclared.

. load;

The required steps in the loading operation are:

(1) conveyor preparation including switching on;

(2) maintain alignment; shuttle cars should follow the CM as it advances; this can be treated as a continuous alignment process and the same criteria can be used.

. align to feeder;

. unload;

. exchange; change point behavior, basically this command either queries for the behavior of the other shuttle car and decides what to do at the change point (rendezvous or proceed), or it functions passively by checking for a 'green light' only (in this case the Section Level planner assumes the traffic control duty).

There might be a possibility for having two change points, one for the loading change out, and another for the dumping change out.

. shuttle car shut down;

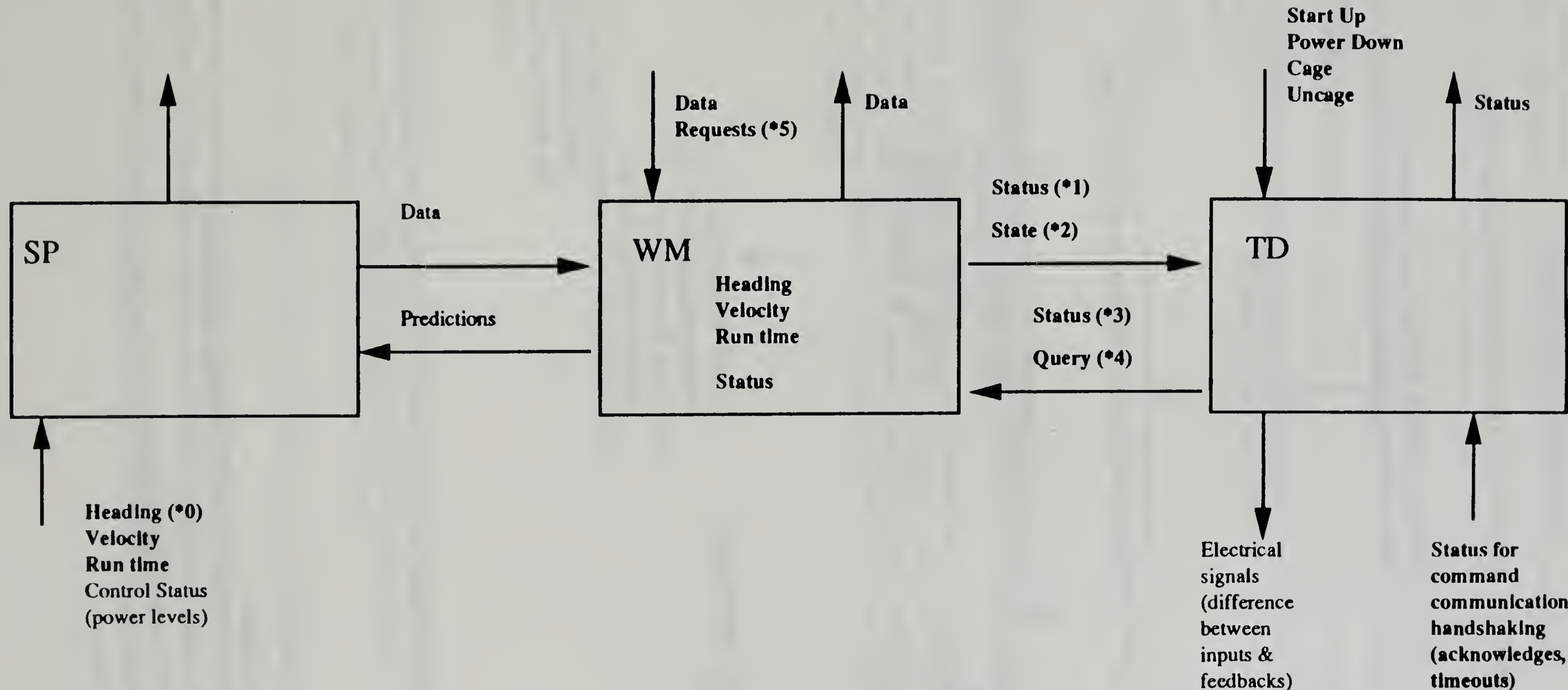
. backout (B);

B: backout location.

. shuttle car shut down;

ACTUATOR LEVEL

GYRO SUBSYSTEM



*0 **Bold faced variables are BOM specified commands; responses packets such as CAP (Command Acknowledge Packets), CECP, CEFP, and CFP are included when applicable.**

*1 status of the other subsystems (for synchronization purposes)
*2 feedback of the state of the world as a response of the executor query
*3 executor compares the world current state and the input commands and posts new states
*4 planner requests for evaluations, executor queries for new states
*5 data/status requests may come from either upper WM or TD;

APPENDIX III An Example of Mapping BOM/NET into RCS

Appendix IV [Jo 82][26]

Start Up Sequence of The J16 CM Continuous Miner

With all breakers closed, tram off, and motors off, turn on the main control switch[27]

↓

switch on pump motor[28]

↓

pump coil energized, causing the electrical interlock to close

↓ (left branch)

hydraulic pump switch held in 'run' position, pressure builds up by the gear pump, and the hydraulic system is controllable

↓

switch on/off hydraulic appendages (parallel controllable)

↓ (right branch)

the electrical circuit[29] voltage is up and the electrical system is controllable

↓

switch for the tram (12 control positions)[30], the conveyor & gathering head (same switch), and the cutting head (Both the cutter motor and the pump switch should be held in the 'start' position to start the cutter[31]).

---

[26]p. 15 of the Introduction Chapter

[27]There is another 'control' switch which is left 'off' in remote control cases.

[28]Pump and Traction use the same switch.

[29]p. 27 and p. 33, Electrical System of the Reference

[30]p. 36, Introduction, per Reference

[31]p. 15, Introduction, per Reference

NIST-114A
(REV. 3-89)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NUMBER
NISTIR 90-4271

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE
MARCH 1990

4. TITLE AND SUBTITLE
Hierarchical Real-Time Control Task Decomposition for a Coal Mine Automation Project

5. AUTHOR(S)
Hui-Min Huang

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)
U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)
U.S. Bureau of Mines
Cochrans Mill Road
P.O. Box 18070
Pittsburgh, PA 15236

10. SUPPLEMENTARY NOTES

☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This paper describes a systematic approach to hierarchial task decomposition and planning. In particular, the methodology can be used to design a complex system which receives goals from the external world, performs intelligent planning, and commands the actuators to achieve the goals. This document was written as a part of the "Architecture for Internal Control of Mining Machines" project.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
automation; Continuous Miner; hierarchy; level; mine; real-time control;plan; state transition diagram; sump; task command; task decomposition; trim

13. AVAILABILITY

[X] UNLIMITED
[ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
[ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
[X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES
60

15. PRICE
A04

ELECTRONIC FORM