A Hierarchical Real-Time Control System for Use with Coal Mining Automation[1]

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ABSTRACT: This paper describes a systematic approach to the design of a hierarchical control system for mining automation. In particular, the methodology can be used to design a complex system which receives goals from the external world, evaluates the current world situation through an interactive sensory data assimilation process, performs intelligent planning, and commands the actuators to achieve its goals. The operator interaction capability is also emphasized.

1. INTRODUCTION

The National Institute of Standards and Technology's (NIST) Robot Systems Division has been developing the Real-Time Control System (RCS) [Albus 1982] methodology since 1980. The RCS methodology emphasizes a hierarchical software architecture for real-time sensory interactive control systems. This methodology has been applied to various large projects including the NIST Automated Manufacturing Research Facility (AMRF) [Simpson 1983], the NASA/National Bureau of Standards (the former name of NIST) Flight Telerobot Servicer (FTS) [Albus 1987], and the Defense Advanced Research Projects Agency (DARPA)/NIST Multiple Autonomous Undersea Vehicle (MAUV) [Albus 1988], etc.

This paper discusses how the NIST Robot Systems Division's RCS methodology can be adapted to a coal mining real-time control system architecture, the Mining Automation Standard Reference Model (MASREM) [Albus 1989].

The overall control architecture of MASREM is generic and therefore may be applied to any mining operation. The emphasis here has been placed on a continuous mining machine [Penn State 1988].

2. MODEL OF AN INTELLIGENT MACHINE

The basic model behind the RCS technology is the intelligent machine system, as shown in figure 1. An RCS interacts with an operator at its highest level, where it receives a compound goal, at the lowest level it acts on the environment to achieve the goal. Internal to the system, perception of the situation of the world is obtained through a hierarchical sensory data assimilation process combining the detected events and the predicted states. Plans are selected according to the situation evaluation process at each level. On the

[1]Presented at the Fourth Conference on the Use of Computers in the Coal Industry, Morgantown, West Virginia, June 1990.

Planning and Execution side of the model, hierarchical and heterarchical task decomposition, as well as temporal and spatial task decomposition occur. Actuators execute the lowest level tasks to achieve the system's goals.

The MASREM is a hierarchical architecture, as shown in figure 2. A different fundamental operation is performed at each level. At the Actuator Level, outputs are electrical currents, voltages, hydrodynamic pressure, etc. At the Primitive Level, mechanical dynamics are computed. At the Elementary-Move (or E-Move) Level, motion pathways that are free of collisions and kinematic limits and singularities are determined. At the Equipment Level, tasks on objects are decomposed into strings of symbolic "elementary" moves. At the Section Level, tasks to be performed typically require the coordination of more than one piece of mining equipment depending on the mining method. The responsibility of the Production Level includes the allocation of resources to the assigned production and support tasks. At the Facility Level, the managing and coordination of the performance of all mining and support operations within the mine take place. These levels are described in greater detail in Section 3.1.

Successive transitions in coordinate frames or resolutions can be seen among different hierarchical levels. 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 typically is required for different levels. A mining operation can be specified by the production tonnage required at the highest level. Tasks are then decomposed at a lower level; to accomplish numerous subgoals, at some level a task may be defined in terms of commands to produce coal in a certain area of the coal seam, at a lower level tasks are decomposed in terms of the coordinate position where coal is to be cut. At even lower levels, the mining sequences are defined as to the number of cuts to make, the number of sumps to make, all the way down to the amount of tram motor current for the distances involved. Lower level tasks must also deal with functions to be performed in a three dimensional world. For example, lower-level coal mining tasks must be concerned with the height of the coal seam to be cut and transforming commands from higher tasks requiring the cutting of coal (of some thickness) into tasks defined in terms of an initial boom position angle and the number of degrees of shearing angle to cut. 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. RCS, in most cases, is flexible as to which reference frame each level should use. But the key point is that at the highest level, a global coordinate frame is used, and at the lowest level, the individual actuator coordinate frames are used. Developers should be aware that coordinate transformations are used throughout an RCS design in order to simplify computations and to facilitate sensor fusion and model matching.

A similar transition in time domain can also be seen. The upper levels deal with plans or events that cover greater periods of time but with less detail, while the lower levels deal with specific tasks or events that cover shorter periods of time.

3. THE MASREM ARCHITECTURE

The MASREM architecture is a three-legged hierarchy of subsystems (each includes multiple computing modules, as shown in figure 3), serviced by a communications system and a physically and functionally distributed global memory, and interfaced to operator workstations and other I/O devices. Conceptually each subsystem has three functions: Sensory Processing, World Modeling, and Task Decomposition. The Sensory Processing function deals with filtering, correlation,and integration processes so that external world features and situations can be extracted. The Task Decomposition function selects and executes the subsystem's tasks. The World Modeling function stores information, answers queries, evaluates situations and makes predictions.

3.1 Functional description of hierarchical levels

In the RCS methodology, each level has specific functions that it performs [Albus 1988, Albus 1987]. These levels from the bottom up are:

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 sensory processing function for this Level is to receive signals from each individual sensor and process them (e.g., the gyroscope readings).

2) Primitive Level: The primitive level is the dynamic control level. The task decomposition function for this level deals with all the dynamic computations, such as computing the maximum allowable 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.

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 [Baumeister 1978]). 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. 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.

4) Equipment Level: The equipment level includes subsystems representing physical entities (e.g., a CM). However, physical entities performing only very simple functions may not be modeled as an equipment-level subsystem. Multiple simple functions can be combined together to form a more complex physical entity which can be modeled as a subsystem in the equipment level. At many mines, scoop cars combine the functions of cleaning coal, spraying rock dust on mined surfaces, and supply transport.

Tasks received for the equipment level are defined in terms of single pieces of equipment acting on single target objects (as compared to subsystems act on object features at the E-Move 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 deal with tasks involving multiple pieces of equipment.

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 as well as supporting operations may be running in parallel in a large coal mine, and each would need a 'set' of Section Level subsystems.

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

3.2. Task decomposition - TD modules

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. Task decomposition involves both a temporal decomposition (into sequential actions along the

time line) and a spatial decomposition (into concurrent actions by different subsystems). Therefore, it is sufficient to describe a task decomposition between any two successive levels as: the higher level sends down "what needs to be done", and the lower level generates "how it can be done".

Each TD module at each level consists of three sublevels:

1) a job assignment manager JA,

2) a set of planners PL(i), and

3) a set of executors EX(i).

These three sublevels decompose the input task into both spatially and temporally distinct subtasks as shown in figure 4.

1) Job Assignment: The job assignment manager JA is responsible for partitioning the task command TC into (s) spatially or logically distinct jobs to be performed by (s) physically distinct planner/executor mechanisms. At the upper levels the job assignment module may also assign physical resources against task elements. The output of the job assignment manager is a set of job commands JC(s).

2) Planners: For each of these job commands JC(s), there exists a planner PL(s) and a executor EX(s). Each planner PL(s) is responsible for decomposing its job command JC(s) into a temporal sequence of planned subtasks PST(s,u) as shown in figure 4.

Planning typically requires evaluation of alternative hypothetical sequences of planned subtasks. As shown in figure 5 the planner hypothesizes some action or series of actions, the world model predicts the results of the action(s) and determines the value of some evaluation function EF(s) on the predicted resulting state of the world. This evaluation function is sometimes called a cost-benefit analysis or objective function. The hypothetical sequence of actions producing the evaluation function EF(s) that gives the best value is then selected as the plan PST(s,u) to be executed by the executor EX(s).

An RCS plan can be described by one or a series of State Transition Diagrams, as shown in figure 6. This "Room & Pillar Advance" plan is 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 the desired location, otherwise a time-out signal would be issued and another navigation plan would be selected and executed first.

This Plan describes a cut and load operation. The conveyor boom at the rear end of the CM is to be aligned with the haulage unit first, 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, or an external pause signal has been received.

3) Executors: Each executor EX(s) is responsible for successfully executing the plan PST(s,u) prepared by its respective planner PL(s). If all the subtasks in the plan PST(s,u) are successfully executed, then the goal of the original task will be achieved. The executor operates by selecting a subtask from the current queue of planned subtasks and outputting a subcommand STX(s,t) to the appropriate subordinate TD module at time (t). The EX(s) module monitors its feedback FB(s,t) input in order to servo its output STX(s,t) to the desired subtask activity.

The feedback FB(s,t) also carries timing and subgoal event information for coordination of output between executors at the same level. When the executor detects a subgoal event, it selects the next planned subtask from the queue.

Executor output STX(s,t) also contains requests for information from the world model module, and status reports to the next higher level in the TD module hierarchy. The feedback FB(s,t) contains status reports from the TD module at the next lower level indicating progress on its current task. As a minimum, these reports provide a handshaking acknowledgment of receipt of the subtask command and an echo of the unique identification number of the command currently being executed. This enables the EX(s) process to know that the subtask output given has been received and is being executed. The

EX(s) process generates error reports if time-outs or failures in handshaking with the TD module at the next lower level occur.

3.3. World modeling - WM modules

The major functions for the WM modules are to Remember, Estimate, Predict, and Evaluate the state of the world.

The World Model contains the system's best estimate and evaluation of the history, current state, and possible future states of the world, including the states of the system being controlled. These features may be stored in the World Model in a representation of mathematical models. For example, the rail car motion model, the subsidence prediction model, etc. The World Model includes both the WM modules and a knowledge base stored in global memory where state variables, maps, lists of objects and events, and attributes of objects and events are maintained.

As shown in figure 7, the WM modules at various levels:

1) Maintain the global memory knowledge base keeping it current. The WM modules update the knowledge base based on correlations and differences between model predictions and sensory observations. This is shown in more detail in figure 8.

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

3) Answer "What is?" questions asked by the planners and executors in the corresponding level TD modules. The task executor requests information about the state of the world and uses the answers to monitor and servo the task and/or to branch on conditions to subtasks that accomplish the task goal.

4) Answer "What if?" questions asked by the planners in the corresponding level TD modules. As shown in figure 5, the WM modules predict the results of hypothesized actions.

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

3.4 Global memory

Global memory, a part of the World Model, is the database wherein is stored knowledge about the state of the world including the internal state of the control system.

The knowledge in the global memory consists of:

1) Maps which describe the spatial occupancy of the world. A map is a spatially indexed database showing the relative position of objects and regions. At different levels the maps have different resolution. Map overlays may also contain value functions such as utility, cost, risk, etc. to be used in path planning and safety.

2) Lists of objects, features, relationships, events, and frames containing their attributes. This database is indexed by name. Object and feature frames contain information such as position, velocity, orientation, shape, dimensions, mass, and other features of interest. Event frames contain information such as start and end time, duration, type, cost, payoff, etc. Recognized objects and events may also have confidence levels, and degrees of believability and dimensional certainty.

3) State variables which identify particular situations. The state variables in global memory are the system's best estimate of the state of the world, including both the external environment and the internal state of the TD, WM, and SP modules. Data in global memory is available to all modules at all levels of the control system.

3.5 Sensory processing - SP modules

The sensory processing leg of the hierarchy consists of SP modules which recognize patterns, detect events, and filter and integrate sensory information over space and time. As shown in figure 9, the SP modules also consist of three sublevels which:

1) compare observations with predictions
2) integrate, correlate and difference over time
3) integrate, correlate and difference over space

These spatial and temporal integrations fuse sensory information from multiple sources over extended time intervals. Newly detected or recognized events, objects, and relationships are entered by the WM modules into the world model knowledge base in global memory, and objects or relationships perceived to no longer exist are removed. The SP modules also contain functions which can compute confidence factors and probabilities of recognized events, and statistical estimates of stochastic state variable values [Huang 1982].

3.6 Operator and programmer interfaces

The control architecture defined here has operator and programmer interfaces at each level in the hierarchy, as shown in figure 3. The interfaces provide the following functions for the users: Control, Observe, Define Goals, Indicate Objects, and Edit Programs and Data.

1) Operator Interface: The operator interface provides a means by which human operators can observe, supervise, and directly control the mining equipment. Each level of the hierarchy provides an interface where the human operator can assume control. The task commands into any level can be derived either from the higher level TD module, or from the operator interface or some combination of the two. Using a variety of input devices such as a joystick, mouse, trackball, light pen, keyboard, voice input, etc., a human operator can enter the control hierarchy at any level, at any "time" of his/her choosing (within restrictions imposed by synchronization and data integrity constraints), to monitor a process, to insert information, to interrupt automatic operations and take control of the task being performed, or to apply human intelligence to sensory processing or world modeling functions (to enter or modify a mining map, for example).

The operator interface terminal may also be used to provide output devices (alphanumeric and graphic CRT's, printers, warning lights, warning sounds, etc.). These output devices provide feedback to the operator and indicate the state of the equipment and the result of the operator's intervention.

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

The programmer interface also exists which allows a human programmer to load programs, monitor system variables, edit commands and data, and perform a broad range of debugging, test, and program modification operations.

2) Operator Control Interface Levels: If the human operator enters the task decomposition hierarchy in the middle the Actuator Level, he/she must use individual joint position, rate, or force controllers.

If the human enters the task decomposition hierarchy above the Actuator Level (input to the Actuator Level), he/she can use an appendage controller to perform resolved motion force/rate control or he/she can use function buttons to actuate or deactivate subsystems or movements.

If the human enters above the Primitive Level, he/she can simply indicate safe motion pathways, and the mining control system will compute dynamically efficient incremental movements.

If the human enters above the E-Move Level, he/she can graphically or symbolically define key positions, or using a menu, call for elementary cutting head or machine transport movements (E-Moves) such as <navigate(A,B,C, ...)>, <sump(depth, height)>, etc. This may be done using an interactive graphics display with a joystick, mouse, track ball, light pen, or voice input.

If the human enters above the Equipment Level, he/she can indicate objects and call for tasks to be done on those objects, such as <continuous miner reset>, <continuous miner cut_load_pause>, <shuttle car unload>, etc. This may be done using cursors and graphic images overlaid on television images.

If the human enters above the Section Level, he/she can reassign mining machines to different mine sections, insert, monitor, or modify plans that describe equipment task sequences, define coal preparation, etc.

If the human enters above the Production Level, he/she can reconfigure all mining priorities, change mining requirements, enter or delete jobs, and change the mining operations schedule.

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

3.7 Safety system

The mining machine control system should incorporate a safety system which can prevent the mining machine system from entering forbidden volumes, both in physical space and in state space. This safety system should always be operational so as to prevent damage to the mining machine, surrounding structures or humans.

4. DEVELOPMENT OF THE MINING AUTOMATION FUNCTIONAL HIERARCHY

In designing an RCS control system, 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 functional hierarchy for the system can be developed.

4.1 Development guideline

A functional hierarchy lays out all the necessary functional modules (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:

1) 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 a functionally integrated coal mine, a Facility Control Level is required as the highest level for the control system, as shown in Figure 2.

2) Pre-Defined Functional Requirements for Each Level - In the RCS methodology, each level has specific functions that it performs. The functional requirements specified in Section 3.1 determine the existence of many subsystems in the hierarchy, such as each piece of equipment.

3) Existing Facilities and Resources - The NIST RCS must utilize existing equipment (the CM, navigation sensors, etc.) -- this implies the existence of certain Equipment and Actuator Level subsystems. Other existing resources include software (including communication protocols) and machine diagnostic systems. As the system development effort evolves, software reusability and generic software components may become significant concepts in handling existing software resources.

4) Operation Requirements and Functional Coherence - The closely-coupled-face-area operations in a coal mine dictate the need for a Section Mining Operation subsystem in the Section Level to coordinate operations such as, coal cutting (performed by CM's), coal haulage (performed by shuttle cars or continuous haulage units), bolting, etc. (machines being coordinated are decomposed into their respective subsystems in the next lower level, as shown in figures 10 and 11).

5) Environment - The complexity of coal seam formation may affect the requirements of the in-seam guidance subsystems and algorithms, and in turn affect the structure of the hierarchy.

6) 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 Section Mining Operation in the Section level) will have a closed loop at the lowest practical 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 system extensibility[Hu 90-1].

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.

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

Violations to the autonomy and modularity guideline can be seen when different guidelines are applied simultaneously. For example, some navigation sensors used to provide range data for the CM may be physically located on a off-board reference structure. The reference structure may be 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 reference structure.

4.2 The mining automation control system functional hierarchy

Figures 10 and 11 shows the functional hierarchy that is being developed for the automation of coal mining using the guideline described above. Note that this hierarchy is for illustration only. Therefore it does not include all the required functions to represent coal mining automation.

The highest level is a Facility Controller, a central controller for the whole mine. This controller receives a customer order and assigns the production goals to individual extraction operations and the support operations. The Facility Controller also performs management functions such as production efficiency analysis.

At the Production Level, multiple extraction and supporting operations are specified. For each extraction operation, three Section Level controllers are specified: Section Mining Operation, Safety /Ventilation, and Material Handling. Each performs a group of closely related functions. The combination of all these groups of functions highlights an extraction operation. Similarly, a Supporting Operation contains Coal Preparation and Material Handling functions.

At the Equipment Level, functions of a Continuous Mining Machine, a Roof Bolter, a Section Haulage unit, and an Overburden Removal unit (for surface mining only) are coordinated by a Section Mining Operation module. Ventilation and Water Drainage Equipment are included in the Safety/Ventilation Controller.

The Continuous Mining Machine can perform the following major operations: Piloting/Guidance, Coal Cutting, Coal Removal, Main Power Control, and Support. Each is represented by an E-Move Level subsystem. Each E-Move Level subsystem has under it either an appendage control unit or a sensor suite, such as the Drum Control, the Gathering Head Control, the On-Board Heading System, etc. These functions reside at the Primitive Level.

The Actuator Level specifies the control for each individual actuator or the data acquisition mechanism for each sensor. Examples are Drum Extension Valve, Linear Transducer number 1, etc.

5. ACHIEVING AUTOMATION THROUGH INTEGRATION

It is desirable for an automated coal-mining control system to have a functionally distributed but integrated architecture. 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 regarding mining automation 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. The 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, being 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) 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 automated 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.

6. SUMMARY AND CONCLUSION

This paper provides a discussion of the theoretical aspects of the NIST real-time control system architecture as applied to mining. What is being suggested is a logical hierarchical structure for coal mine automation. The basic model behind the RCS methodology, the intelligent machine system, is discussed first. The description of the MASREM architecture includes the predefined hierarchical levels and their functions, the required subsystems for each level, the required computing modules for each subsystem and the functions these computing modules perform, and the human interaction capability.

A key to automation is to have a comprehensive system architecture. MASREM has taken an initial step towards such objective. The MASREM can serve as a conceptual framework to facilitate integration. An integrated system can be approached incrementally from the bottom up in the architecture. Once the initial hierarchy is defined, each subsystem, representing either a piece of equipment or a function, can be automated separately using the RCS methodology, and then integrated into the system. Through this process an RCS automation design can be extended to include different aspects of a coal mining operation.

7. ACKNOWLEDGEMENTS

The paper is an application of RCS methodology. RCS methodology was originated by, and is evolving under, the leadership of Dr. James 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 Mr. Richard Quintero, Group Leader of the Robot Systems Division, and my teammates, Mr. John Horst and Mr. Don Orser, 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 10).

My thanks to Cheryl Hutchins for her careful editing job and Ann Hargett for her assistance in typesetting the manuscript.

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AN INTELLIGENT MACHINE SYSTEM

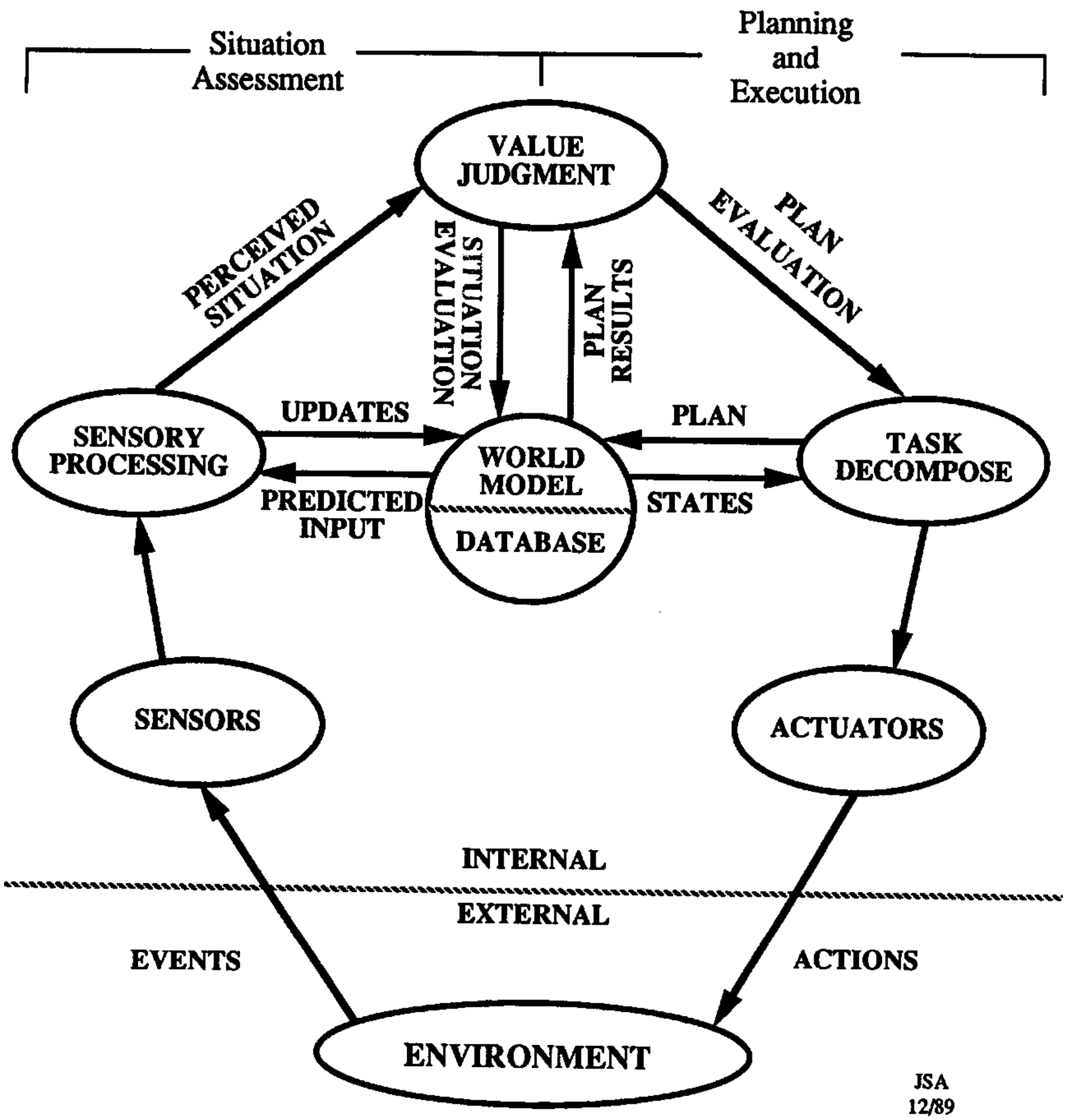


Figure 1: The elements of intelligence and the functional relationships between them.

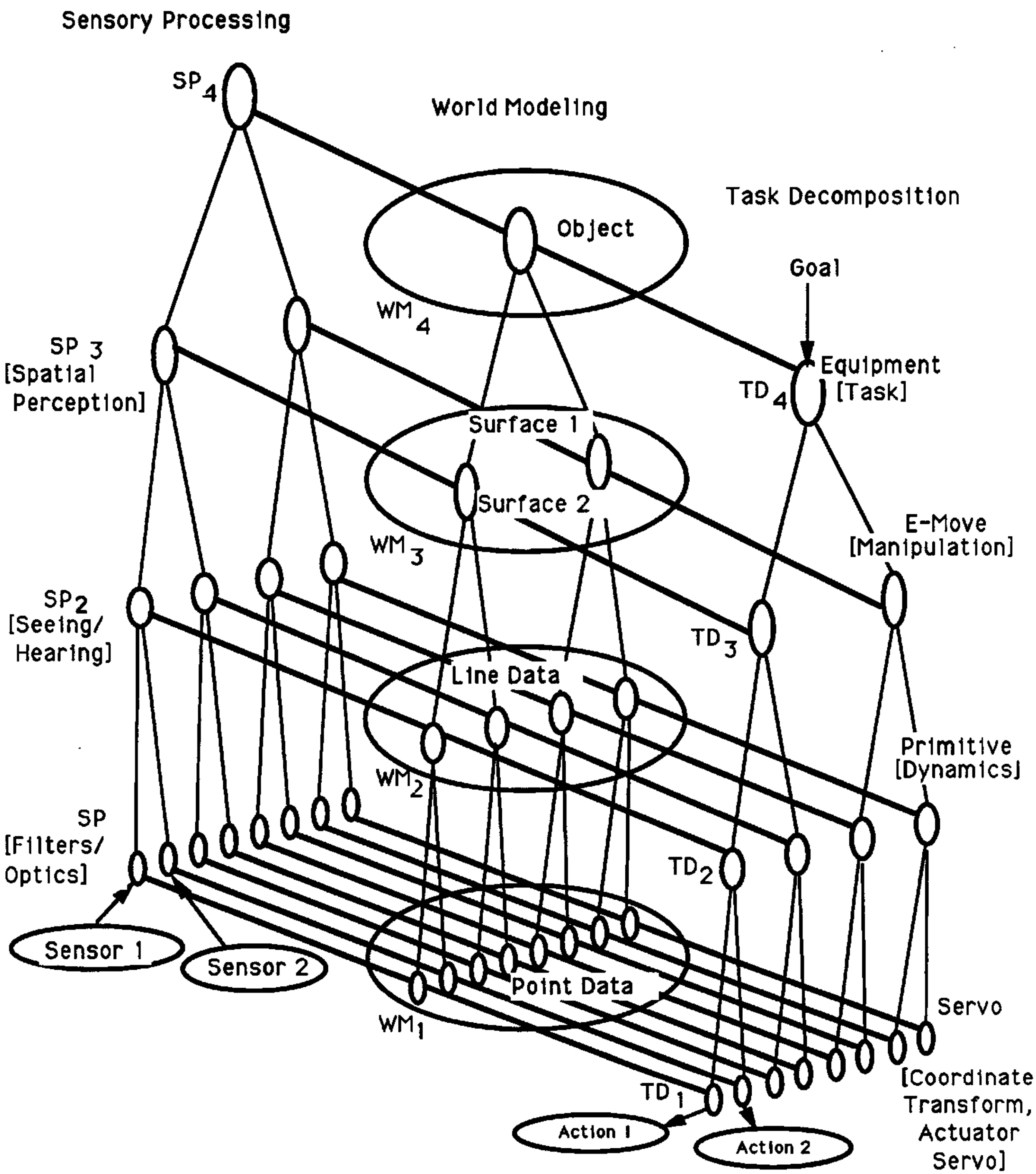


Figure 2: Hierarchical and Heterarchical (Horizontal) Organization of the Real-Time Control System Architecture

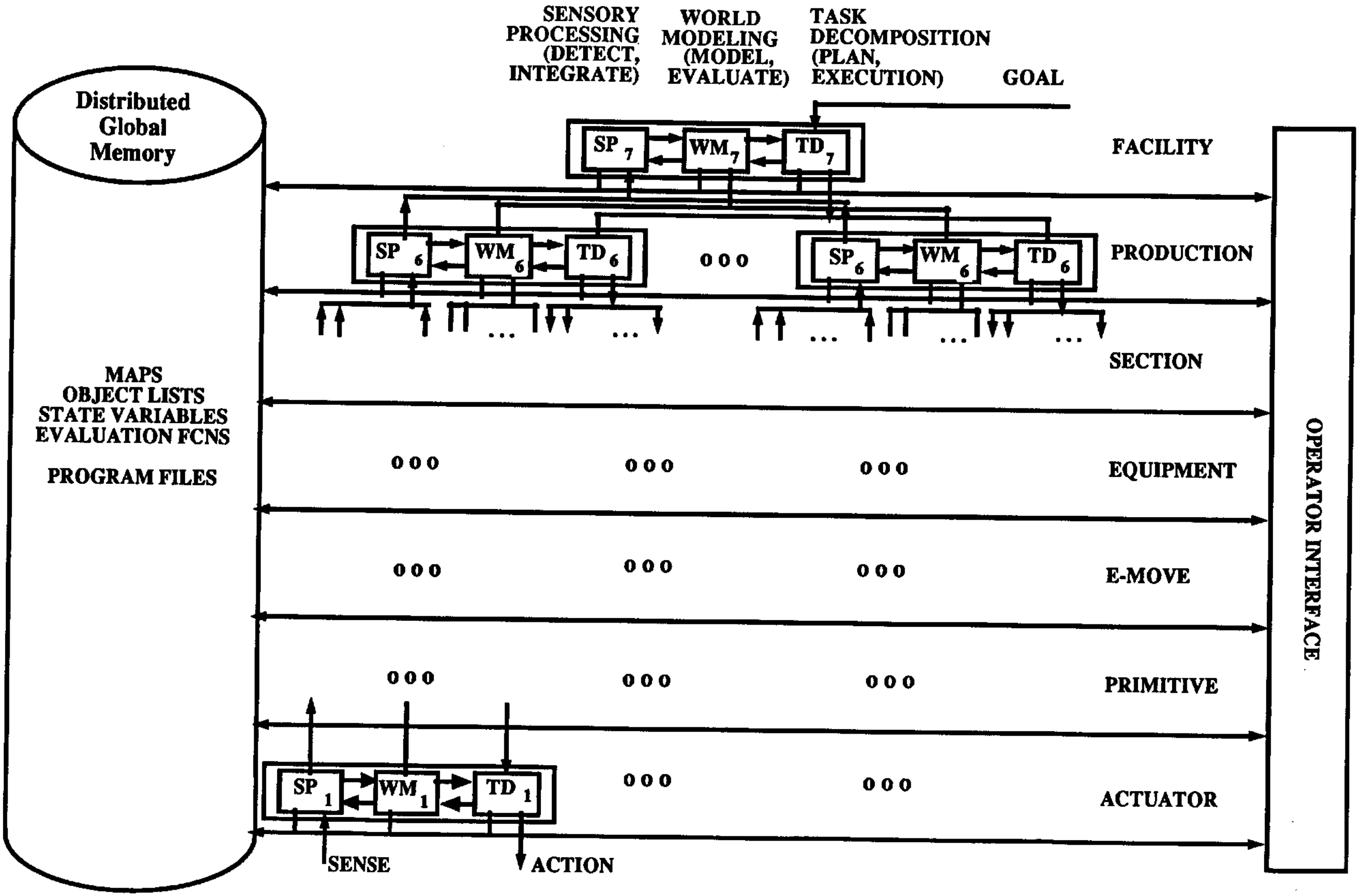


Figure 3: Real-Time Control Architecture Functional View for Each Subsystem

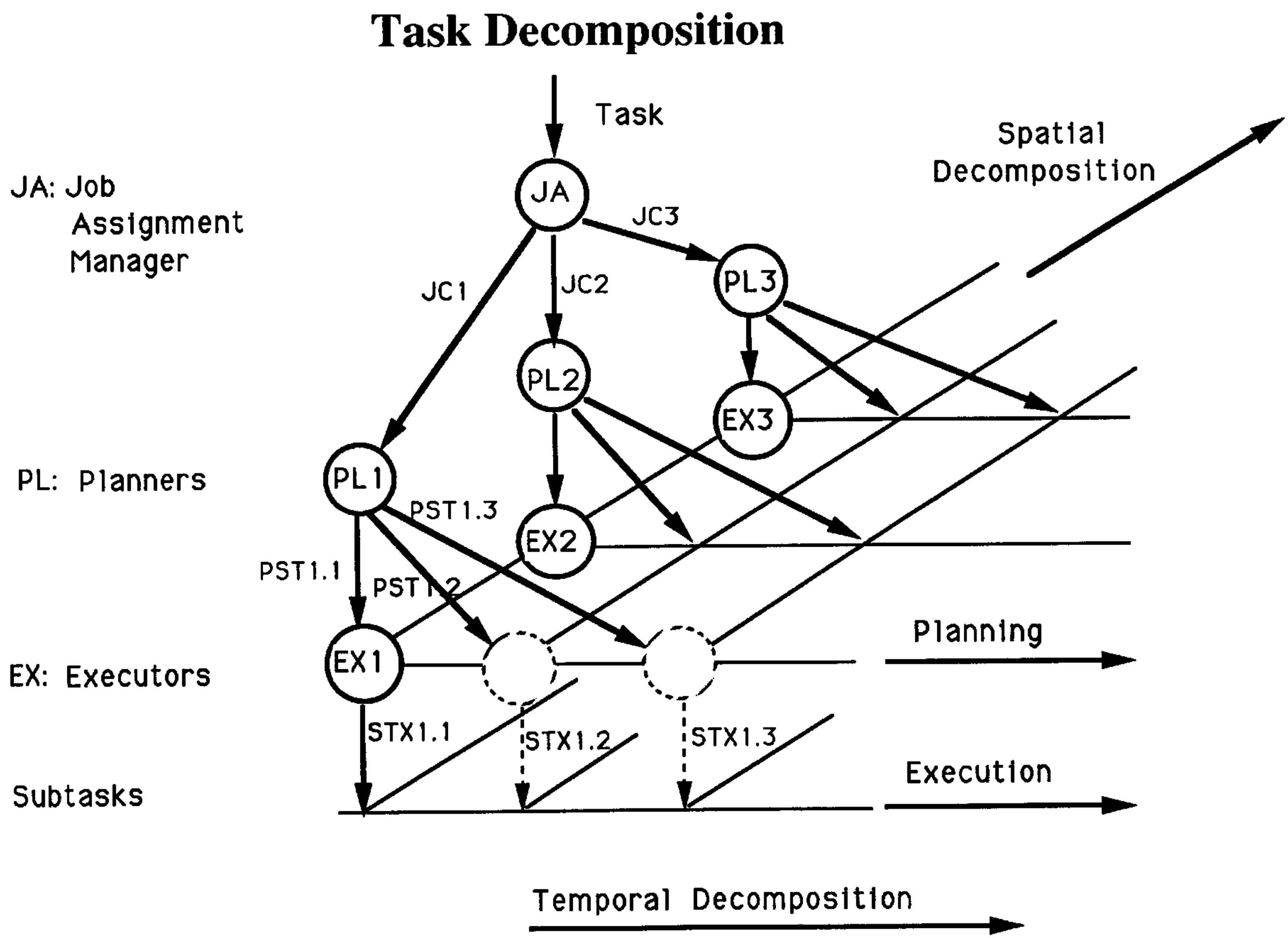


Figure 4: The Task Decomposition Function in an RCS architecture

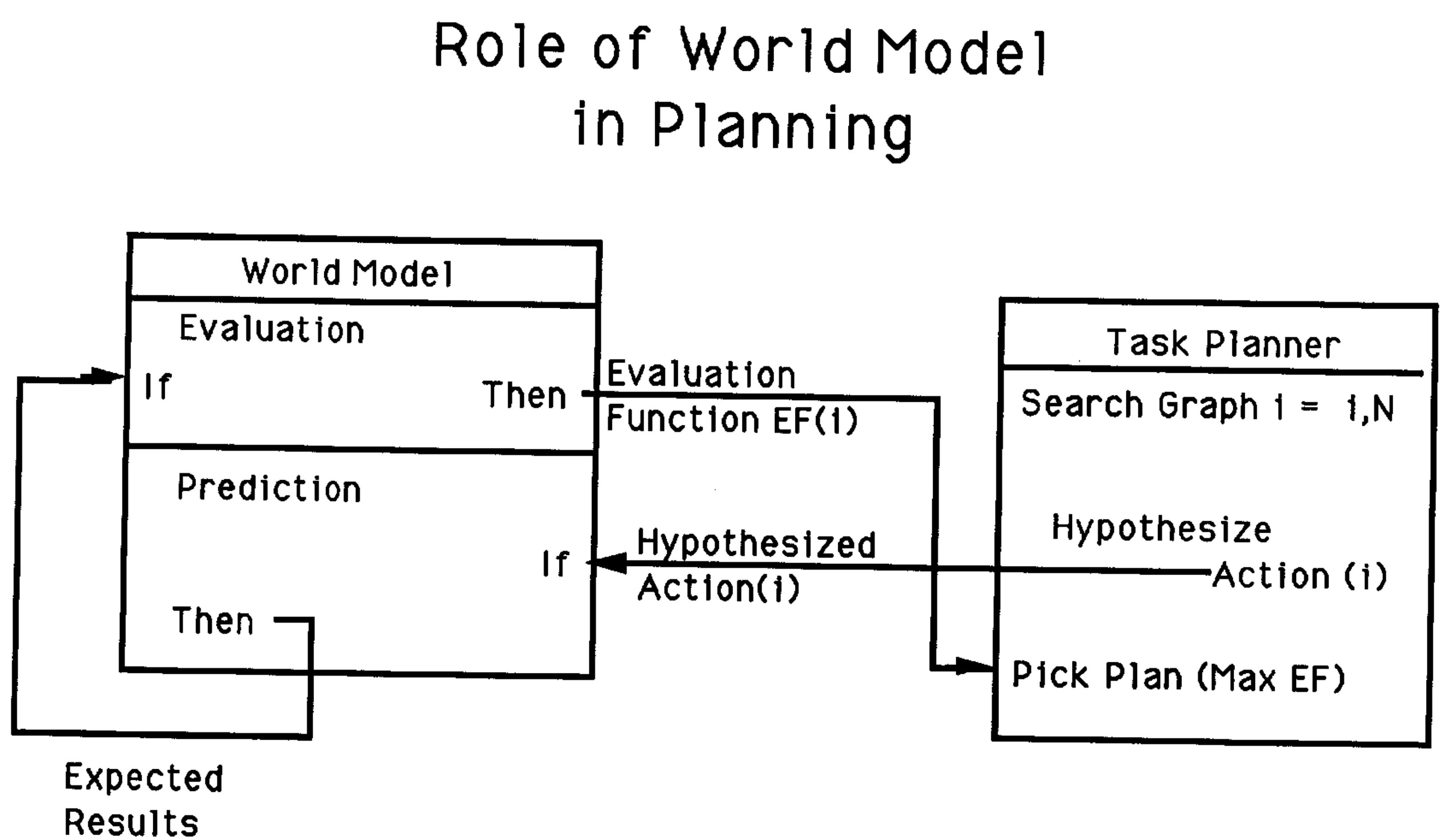
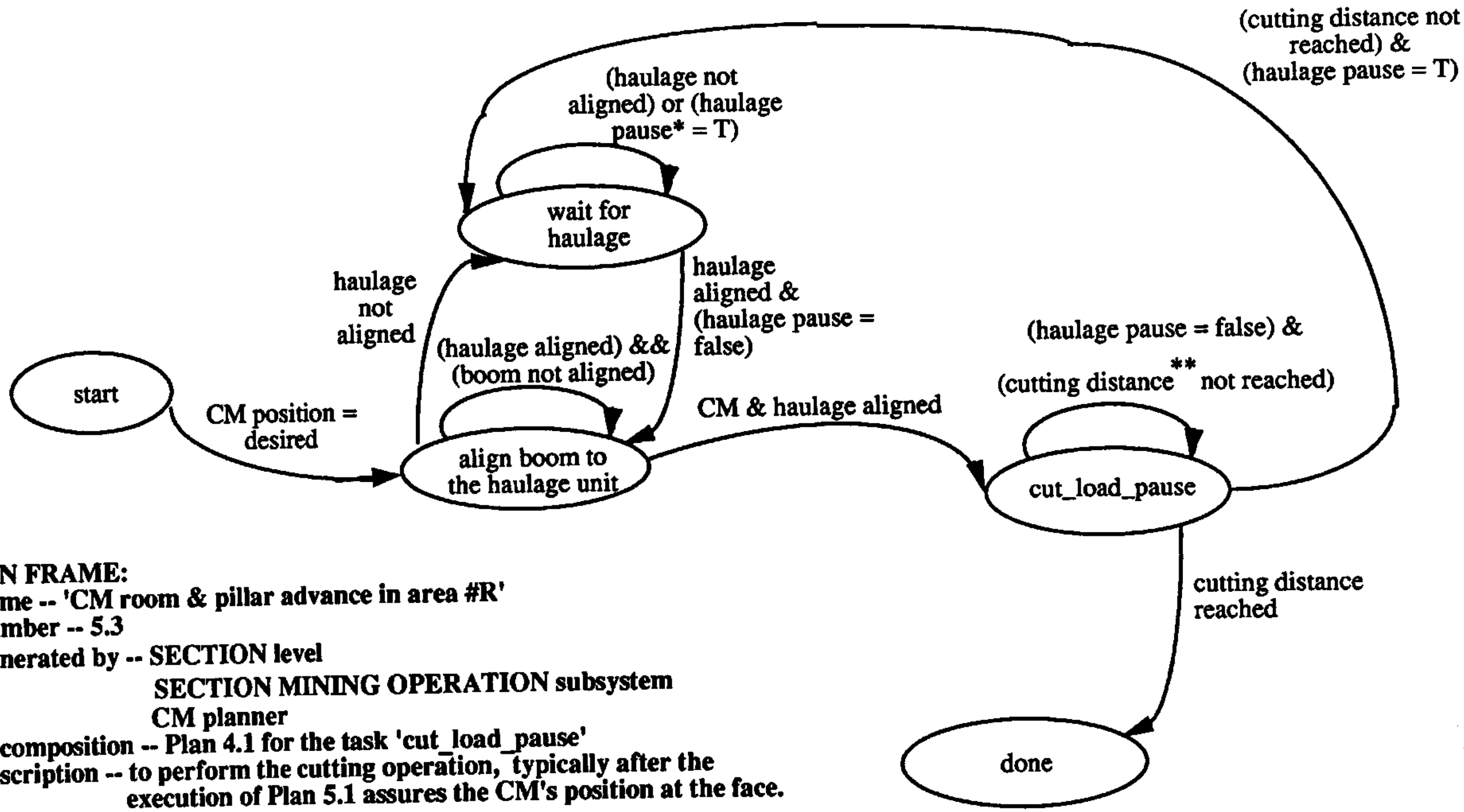


Figure 5: Role of World Model in Planning. Hypothesized Actions Are "What If?" Questions.



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

Figure 6: A Room & Pillar Advance Plan

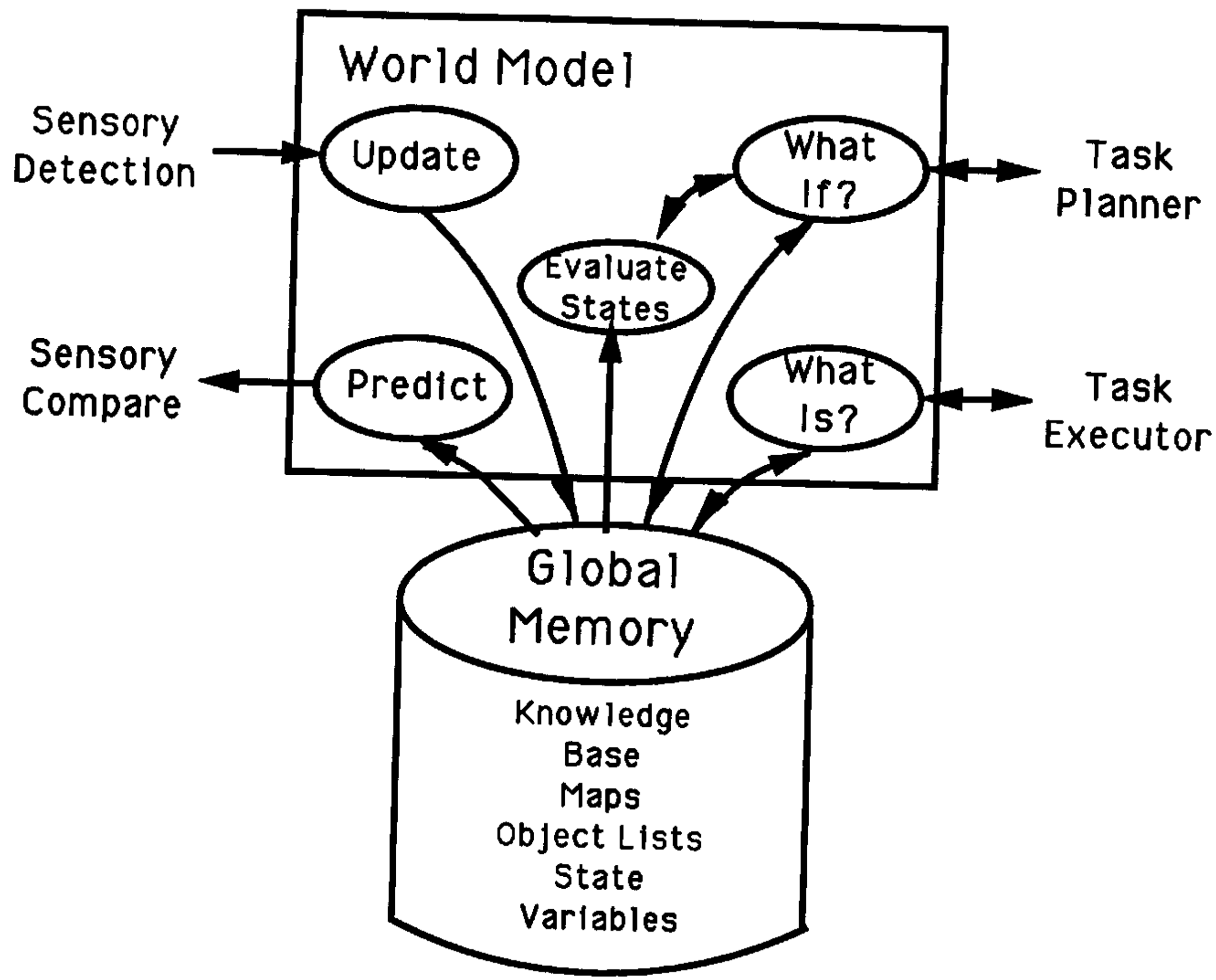


Figure 7: Functions Performed by WM Modules in the World Model

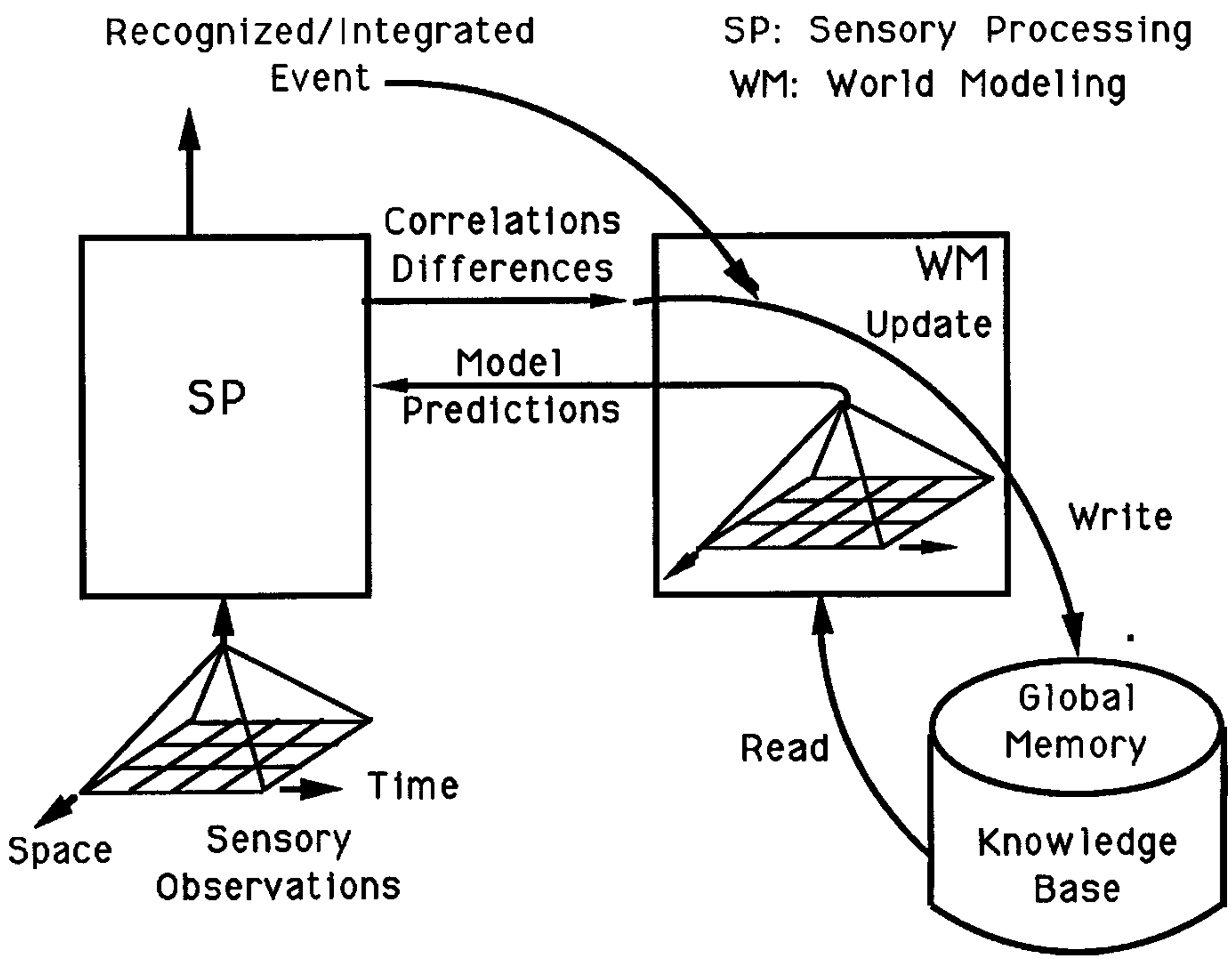


Figure 8: Role Of WM Module in Predicting Sensory Input and in Up-dating Knowledge Base Based on Correlations and Differences between Predictions and Observations

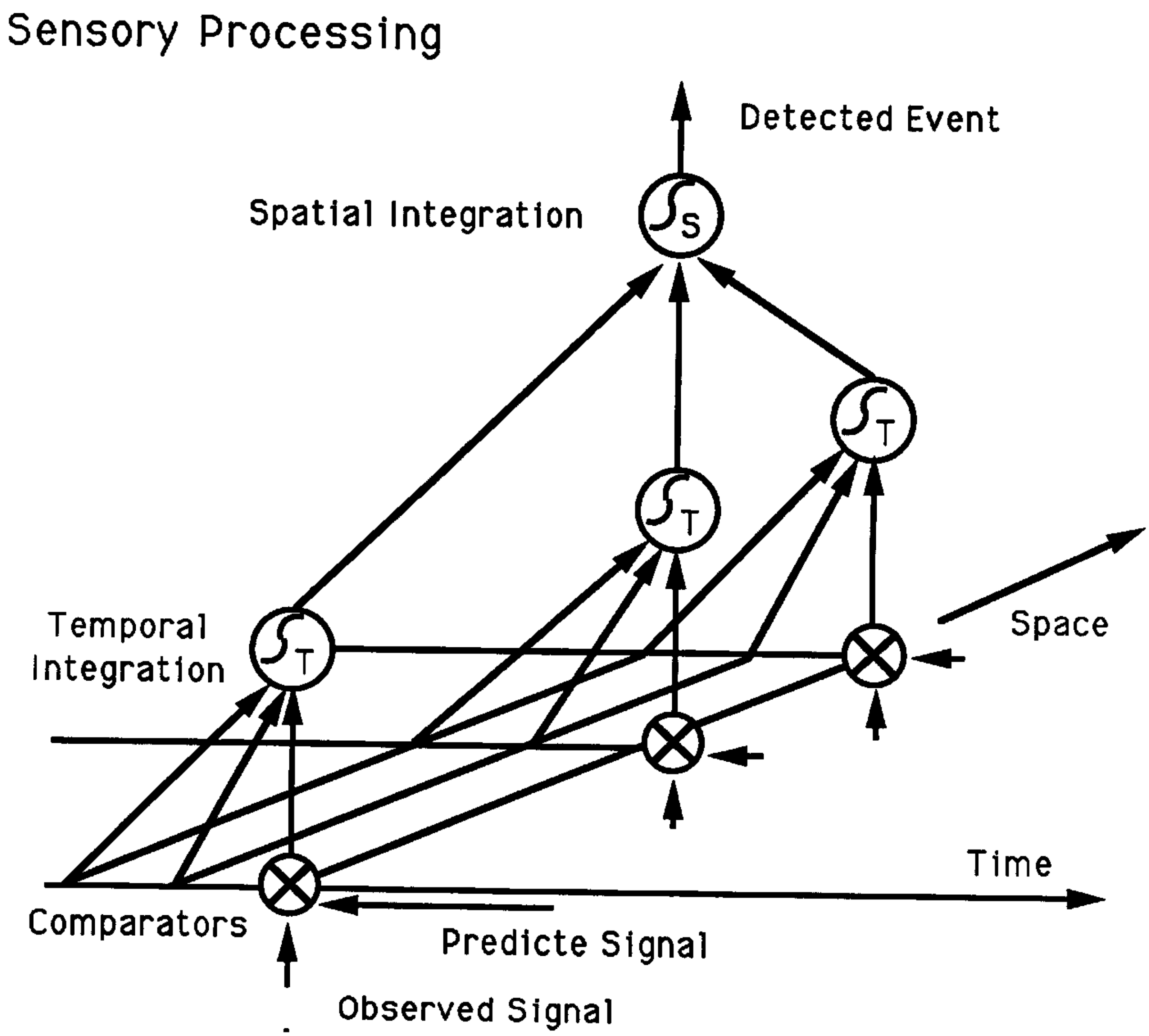


Figure 9: Each Sensory Processing SP Module Performs a Comparison and both Temproal and Spatial Integration

MINE AUTOMATION HIERARCHICAL
REAL-TIME CONTROL SYSTEM

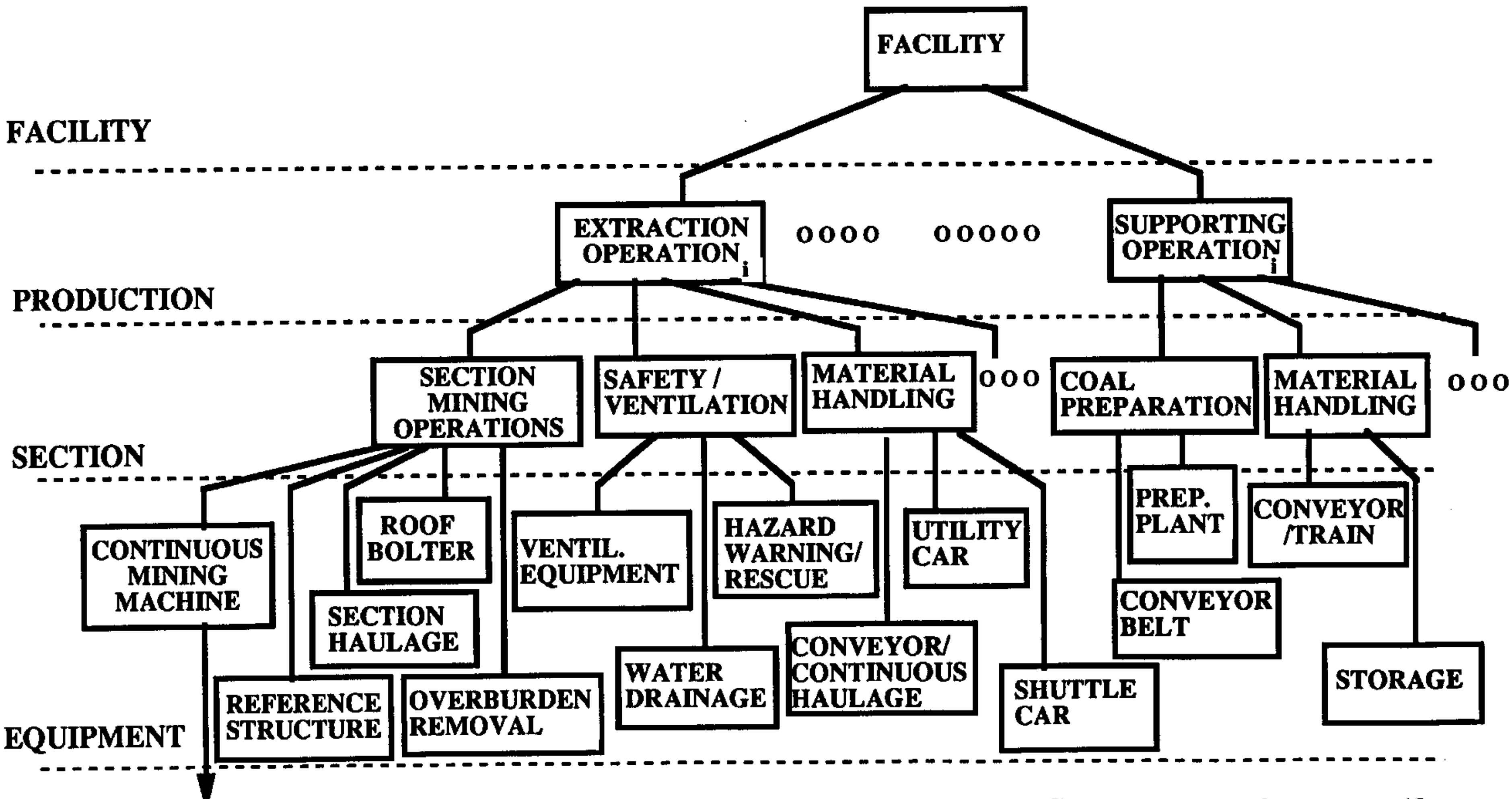
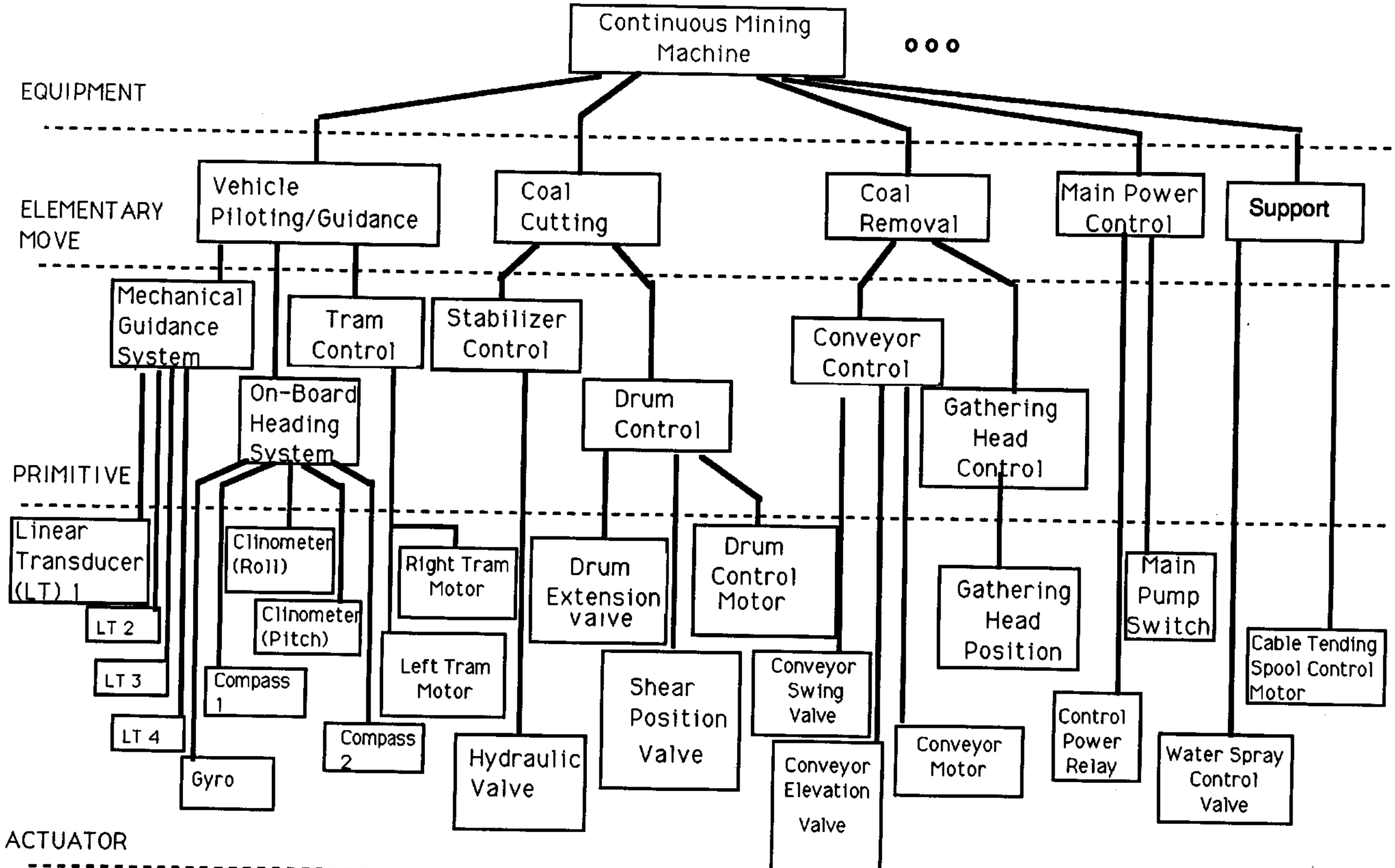


Figure 10: Mine Automation Hierarchical Real-Time Control System Architecture (for Higher Levels)



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 11: Mine Automation Hierarchical Real-Time Control System Architecture (for Lower Levels)