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Guillermo Rodriguez
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INTELLIGENT CONTROL AND ADAPTIVE SYSTEMS

Volume 1196

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INTRODUCTION

This conference provided an overview of the state of the art in intelligent control and adaptive systems. Robotic systems were the primary application domain. Papers were presented in eight technical sessions: Architectures and Operating Systems, Modeling, Perception, Intelligent Control, Neural Networks, Planning, Learning and Adaptive Systems, and Genetic Algorithms.

The session on architectures emphasized issues in task representation and task-directed control as well as distributed operating systems. The session on modeling was based on the premise that in order for a system to behave intelligently it must have a built-in model of the task at hand. Papers in this session discussed global kinematics and statistical mechanics models that govern the behavior of the robot while operating in a constrained object environment. The papers on perception focused on the issues of identification and knowledge representation. The Intelligent Control session explored the topics of simulation, distributed self-organizing intelligent control systems, and control for hand-eye coordination. The papers on neural networks addressed the issues of navigation and tracking, electronic hardware, mechanization of neuroprocessors, and learning algorithms for robot control. The Planning session contained papers on the use of group theory to develop strategies for manipulation. Papers on distributed scheduling and control of mobile robots as well as incidental learning by means of exploration were also presented. The session on learning and adaptive systems contained papers on analysis of neural networks as dynamical systems, connectionist learning and control, and object-oriented simulation for complex adaptive systems. The papers on genetic algorithms described applications to global optimization and to fuzzy-logic control for spacecraft terminal rendezvous.

The conference reviewed the major technical disciplines necessary to design an intelligent system, providing an indication of the state of the art in theory, algorithm development, and computing. It also provided an understanding of research problems of current interest, operating in unstructured environments for example, which have not yet been completely solved and which are topics for future research. The goal of developing intelligent systems will not be easy to achieve. Much has been done, and much more remains to be done. The conference provided one small step toward this goal.

Guillermo Rodriguez
Jet Propulsion Laboratory

Subramanian T. Venkataraman
Jet Propulsion Laboratory

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SESSION 1

Architectures and Operating Systems

Chair
Subramanian T. Venkataraman
Jet Propulsion Laboratory

A control architecture for a Mars walking vehicle

Andrew J. Spiessbach

Martin Marietta Space Systems
Denver, Colorado 80201

1. INTRODUCTION

NASA is studying a Mars Rover Sample Return (MRSR) mission to perform *in-situ* analysis, collection and return to Earth of Martian surface samples. The value of science return from this mission is critically dependent upon the ability of a robotic roving vehicle to negotiate the diverse geology of this planet without incurring accidental damage or vehicle entrapment. Legged locomotion offers the considerable advantages of stability, low power, and traversability over extremely rugged terrain, and legged vehicle design concepts are currently being developed under the MRSR[1] and Pathfinder[2] projects. Semi-autonomous operation of a walking planetary rover entails several unique technical challenges, and places a premium on the system architecture needed to coordinate and control the vehicle actions. A design framework for such a system is provided in the following paragraphs, and is intended for missions where a high degree of autonomy is dictated. It provides a logical computing architecture for rover mobility and local navigation subsystem design by defining a set of functional modules and interfaces to facilitate software and hardware specification.

The control architecture for mobility and local navigation discussed in this paper is based on the system architecture for planetary rovers developed by Smith and Matijevic[3]. The three-dimensional organization of the latter is extended in several ways. First, interaction between modules is made more explicit. In the architecture of Smith and Matijevic, there is no commitment to an explicit model of interaction between functions, levels and tasks. In the current approach, the paradigm of a generalized control loop supplies the fundamental constraint on interactions at each level. Secondly, the basic three-dimensional architecture is extended by the introduction of a more fundamental hidden dimension into the underlying structure. While Smith and Matejivec applied their approach to the general system architecture for the overall rover, the current approach is limited in scope to the specific rover subtasks of mobility and local navigation.

The basic architectural concept and underlying ideas are presented in Sections 2 and 3, where similarities and distinctions between this approach and related architectures for autonomous navigation and robotic control are discussed. In Section 5, an approach is presented for specifying actions to be taken by the mobility and local navigation subsystems of the rover. Suitability of the defined functional architecture for Mars exploration is provided through the example of the Walking Beam[4] rover concept currently under development at Martin Marietta.

2. BASIC ARCHITECTURAL CONCEPT

The traditional approach to building an architecture for a mobile robot is to organize the individual functions into a hierarchical structure. Typically, an afferent processing chain converts observerables directly measured by sensors into the higher-level objects and events required to understand the vehicle's internal state and external environment. This is the "signal to symbol" or "pixels to predicates" process. Similarly, an efferent processing chain successively refines goals into subgoals, and plans into subplans, until the desired action is expressible in primitive commands that can be directly executed by the vehicle's actuators. Higher layers of the control architecture correspond to the higher levels of information abtsractness required to extend the competence of the robot. The hierarchical chain of afferent and efferent processes is closed at its lowest level by transducer interactions with the environment, and is closed at its highest level by the human supervisor that the vehicle serves. The overall closed chain serves as a control loop. The NASA/NBS Standard Reference Model[5] (NASREM) for the Space Station Freedom telerobot control system is a prime example of a hierarchical control architecture. In NASREM, the abstraction hierarchy is complemented by a functional decomposition into fundamental decision-making processes, such as sensory processing and world modeling.

Alternatively, an architecture can be developed by using task elements as the primary dimensions for decomposition of the control problem. A system using a processing decomposition based on task-achieving behaviors has been used to control a mobile robot wandering around unconstrained laboratory areas and computer machine rooms[6].

Decompositions by task and function are not mutually exclusive, since the end does not necessarily determine the means. Simultaneous decomposition is indeed possible, and is advocated in the present approach. In addition to the vertical stratification (low to high levels of cognition) entailed by the abstraction hierarchy, the present architecture is also horizontally decomposed by both function and task.

The three fundamental dimensions adopted in this architecture for decomposing the rover navigation problem are: decision-making task, computational function, and level of information abstractness. The basic 3-D organization is shown in Figure 1. A fourth dimension provides a further decomposition of the problem by partitioning into subsystems corresponding to separate, potentially conflicting goals. Figure 2 shows the princical perspectives for viewing the basic 3-D architecture:

- Control loop viewpoint (horizontal cross sections in the function-task plane),
- NASREM viewpoint (cube face in the task-abstraction plane),
- Task problem-solving viewpoint (vertical cross sections in the function-abstraction plane).

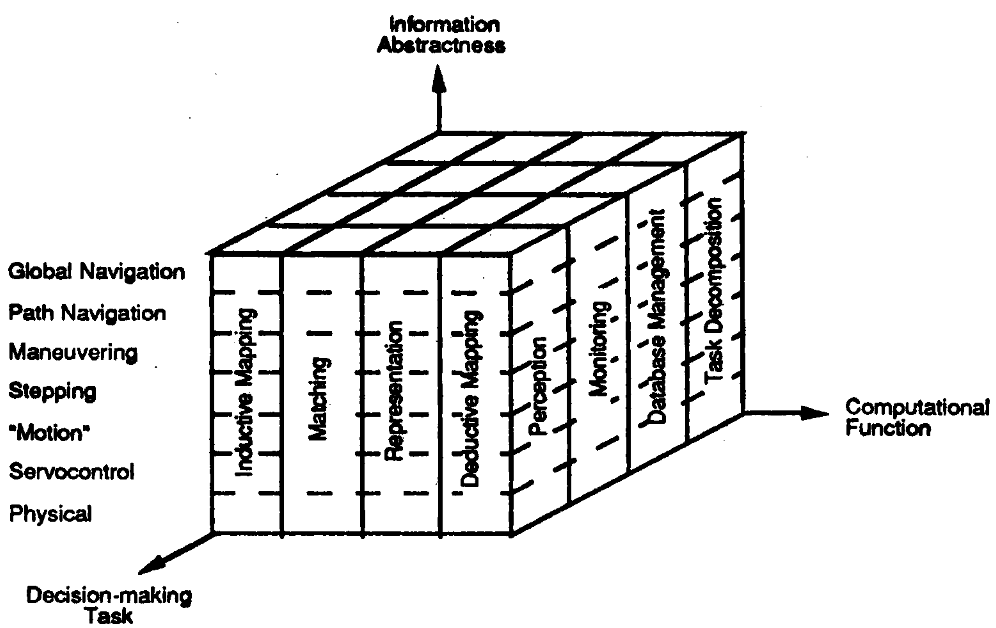

Figure 1. Principal Conceptual Dimensions for Problem Decomposition.

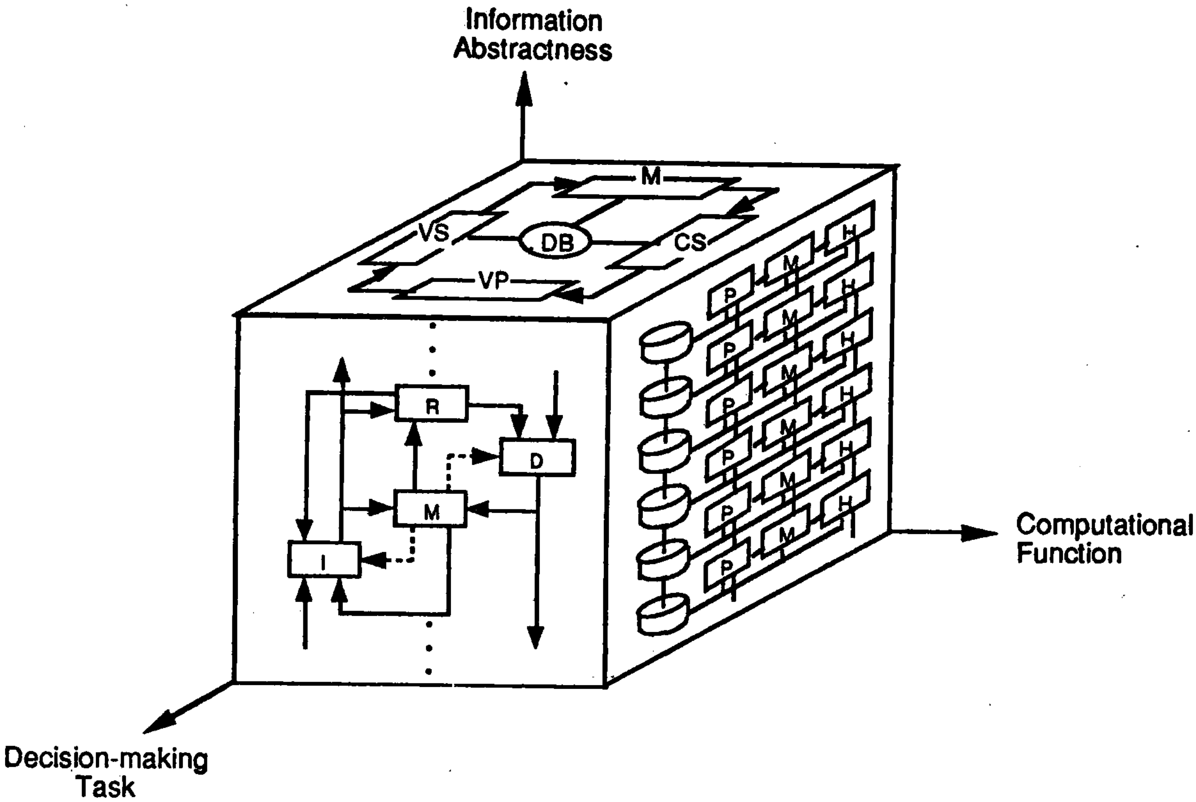

Figure 2. Principal Perspectives on the Control Architecture.

Horizontal slices through the 3-D cube of Figure 2 reveal an abstract control loop operating at each level of the hierarchy. The conventional servocontrol loop elements of plant, feedback sensor, control law and difference operation are generalized to virtual plant, virtual sensor, command synthesis and execution monitoring functions (Figure 3). In addition, a local portion of a distributed database has been incorporated at each layer. The identical form for control loops at different layers provides a recursive organization, where the virtual plant at the Nth layer is equated with the collection of monitoring, sensing, command synthesis, and database functions of the N-1 layer (Figure 4). The recursive aspects of the architecture can also be viewed as a nested set of control loops. This matrix structure composed of (horizontal) functional loop-modules with a nested (vertical) hierarchy of corresponding functions is similar to the architecture for the Intelligent Mobile Autonomous System (IMAS), which used a four-level hierarchy based on information resolution[7]. As shown in Figure 5, the resulting hierarchy of control loops can be visualized graphically as a waterfall flow of data and control.

Projection of the 3-D architecture on to the task and abstraction axes (i.e., the right side of the cube of Figure 2) reveals the basic elements of the NASREM model (slightly modified). The four channels in the present architecture are: Perception, Task Decomposition, Monitoring and Database. Perception subsumes all of the NASREM Sensory Processing hierarchy as well as parts of NASREM's World Modeling channel. The function of monitoring actual states against plan expectations is elevated to a separate hierarchy of units in the present architecture, whereas it was part of the Task Decomposition channel in the Smith & Matijevic and NASREM architectures. In addition,

the hierarchy of modeling modules in NASREM has been split up. The computation of evaluation functions is performed by the monitoring elements as opposed to the modeling modules in NASREM.

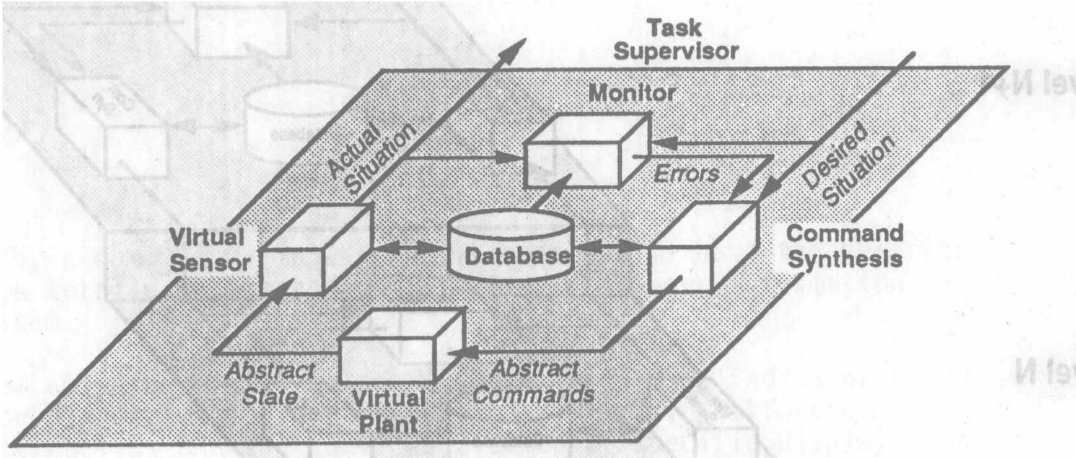

Figure 3. Generalized Control Loop

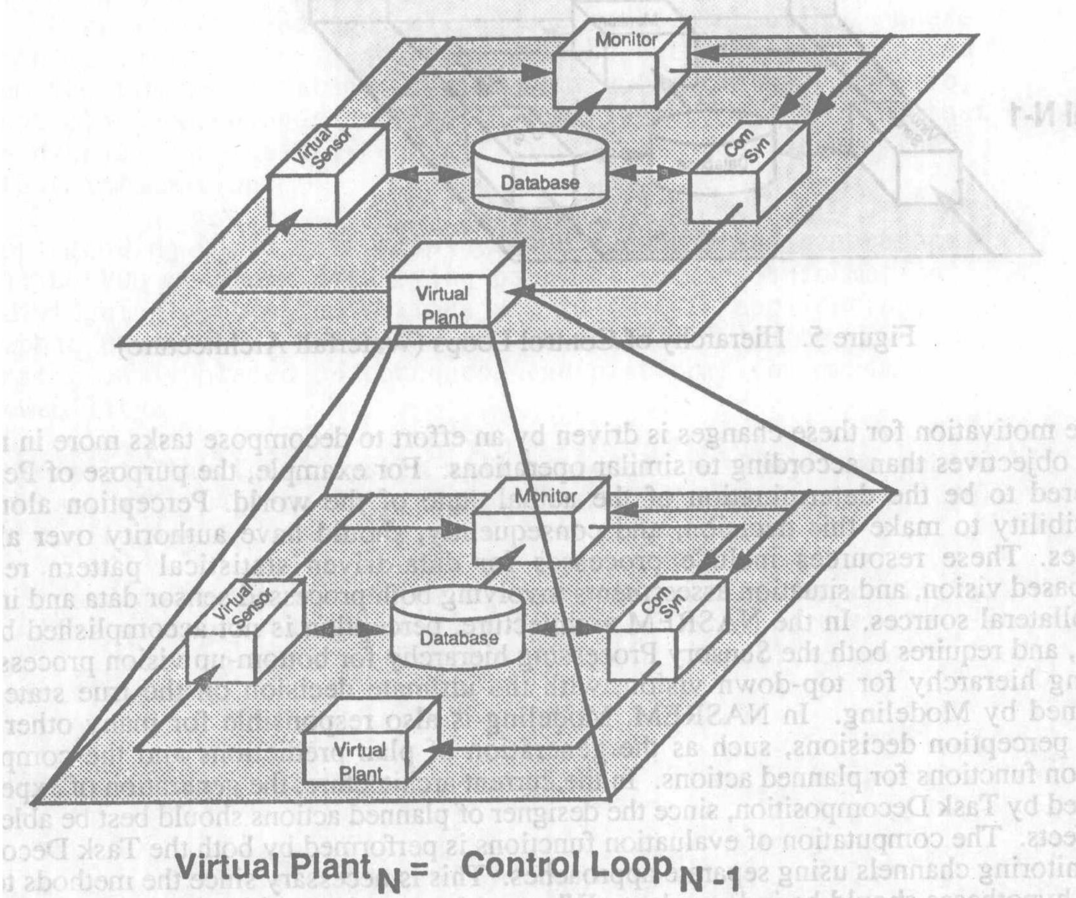

Figure 4. Recursive Relationship Between Control Loops at Different Levels

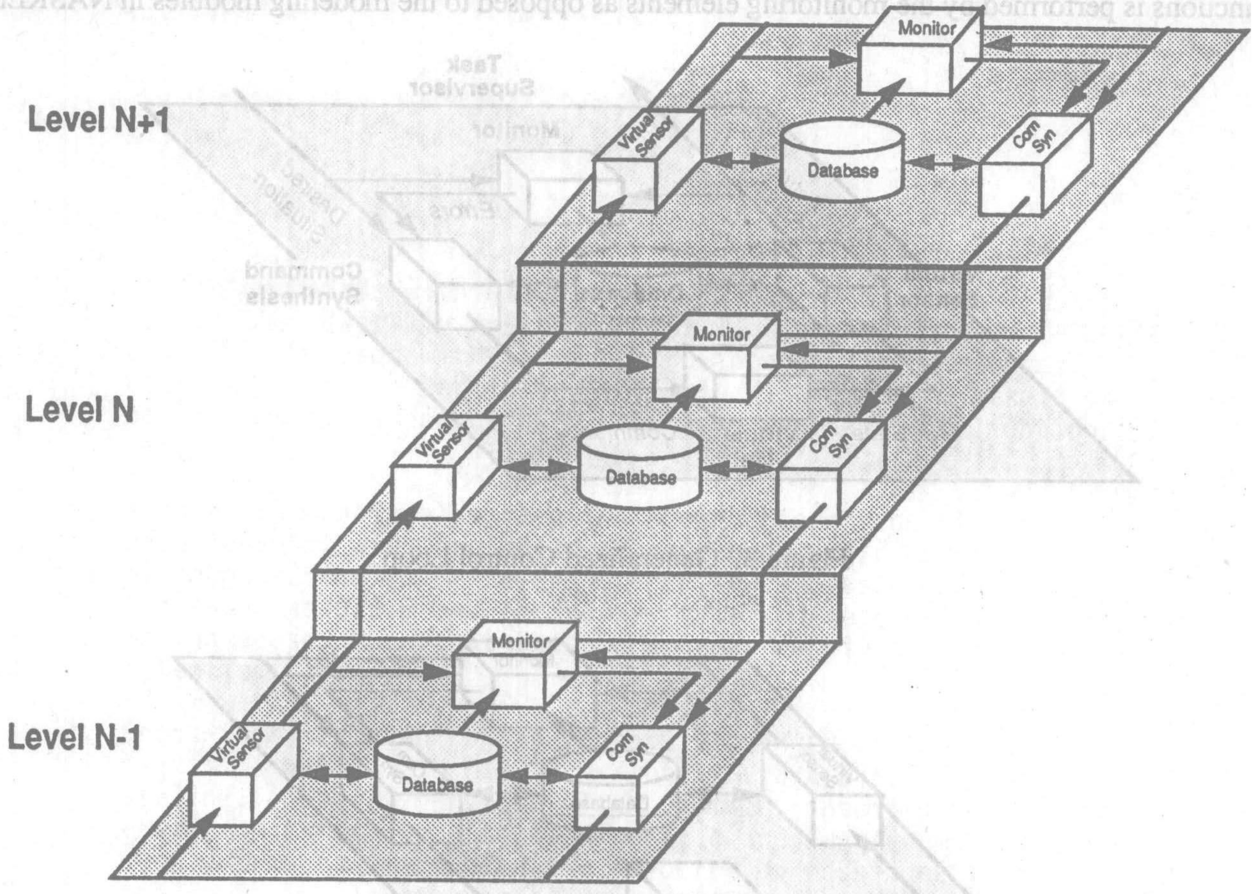

Figure 5. Hierarchy of Control Loops (Waterfall Architecture)

The motivation for these changes is driven by an effort to decompose tasks more in response to distinct objectives than according to similar operations. For example, the purpose of Perception is considered to be the determination of the actual state of the world. Perception alone has the responsibility to make this decision, and consequently, should have authority over all required resources. These resources include processes for data-driven statistical pattern recognition, model-based vision, and situation assessments involving both processed sensor data and information from collateral sources. In the NASREM architecture, perception is not accomplished by any one channel, and requires both the Sensory Processing hierarchy for bottom-up vision processes and the Modeling hierarchy for top-down vision, with the ultimate decision on the true state of things determined by Modeling. In NASREM, Modeling is also responsible for many other functions besides perception decisions, such as the generation of plan predictions and the computation of evaluation functions for planned actions. In the current architecture, the generation of expectations is performed by Task Decomposition, since the designer of planned actions should best be able to predict their effects. The computation of evaluation functions is performed by both the Task Decomposition and Monitoring channels using separate approaches. This is necessary since the methods to generate and test hypotheses should be independent. Whereas the constituent functions in both the proposed architecture and the NASREM model are basically identical, they are aggregated into different sets in the two approaches. Division of responsibility in this architecture is more along the lines of human hierarchies.

Vertical slices through the 3-D cube of Figure 2 normal to the task axis (e.g., the front cube face) show the hierarchical structure from the perspective of the constituent functions entailed by each task. Cross sections through a specific task channel of the NASREM-like hierarchy, such as Task Decomposition, reveal a hidden layer of fundamental processes. The basic NASREM model is consequently extended by the introduction of this third dimension, which further decomposes system elements into a set of fundamental information processing functions: inductive mapping, deductive mapping, matching, and knowledge representation.

Hypothesis generation uses both inductive and deductive mapping methods, thereby permiting independent lines of reasoning. Induction involves the generalization of more abstract information from lower-level or partial forms, and typically requires the pooling of disparate evidence from multiple sources. Deduction involves the operationalization of existing declarative knowledge into a suitable form for logical comparison against more specific data. Declarative data can be either semantic or eposidic, consequently this architecture allows for case-based reasoning as well as the more traditional paradigms (e.g., operator subgoaling). Aggregated incremental results from these methods are simultaneously compared at the various levels of the hierarchy in the matching process, which provides the hypothesis testing function. Matching is critical since it is the source of meaning. Consistency between these tentative hypotheses serves to reinforce confidence and control the overall process. Newly integrated are used to tune the process to the particular problem at hand (feedback) so that more accurate results can be obtained. Iteration is required for the system to converge to a complete and consistent solution. Since tentative results shared among processes are not required to be correct, the process is tolerant of uncertainty.

Decomposition according to subsystem provides a fourth organizational dimension. There is a separate 3-D cube associated with each of the lowest level subsystems in the rover architecture. The principal distinction between subsystems is their difference in purpose. In the present architecture, processes within a 3-D structure have concordant goals; there is little potential for conflict. Functions corresponding to different 3-D architectural cubes have overlapping and potentially conflicting goals. Intra-cube functions can therefore be coordinated by more tightly-coupled control schemes, permitting organization in terms of a hierarchy of control loops. Inter-cube functions require a more loosely-coupled means of achieving global coherence, and consequently, a distributed approach is adopted, as shown in Figure 6.

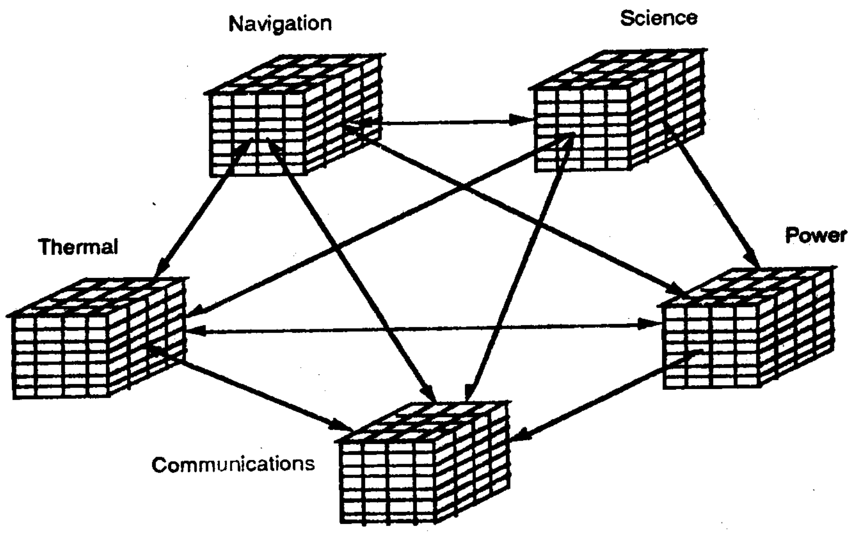

Figure 6. Loosely-coupled Control of Subsystems with Disparate Goals.

3. HIERARCHICAL LEVELS FOR A WALKING ROVER

As shown above, the application of the "divide and conquer" paradigm resulted in an architecture consisting of a cross-coupled hierarchy of closed navigation loops. These loops occur at different levels of abstraction, which in a well-engineered design, correspond to natural breakpoints in the scale of the navigation problem.

Since navigation and locomotion are primarily spatial activities, the layers of the control hierarchy are defined as successively finer spatial differentiations. Six natural spatial scales exist for the walking rovers being considered, and corresponding levels are currently specified as follows: global navigation; path navigation; maneuvering; stepping; step constituent operations (e.g., foot placement, sensor fixation) and servocontrol. For global navigation, the rover is considered a point, and cycle times are asynchronous and on the order of hours to days. For path navigation, the vehicle is considered an extended rigid body. Planning of maneuvers and constituent stepping operations occurs at a scale comparable to the articulated members of the vehicle structure (e.g., translation stride, leg strokes) and are accomplished in minutes or less. The inherent spatial and temporal scales for foot placement operations are a fraction of a footpad dimension and seconds to tens of seconds, respectively. Timelines for servocontrol are of the order of tens of milliseconds.

A six-level decomposition is also provided in the NASREM model, however, the levels suitable for telerobot control are quite different from those selected for legged rover locomotion. The specification of particular levels is also one major difference between the system architecture of Smith and Matijevic and the current approach. Levels in the former approach are very generic, being based on the mathematical features of small state machines: states of the dynamical system; permissible states of the control law; sequences of permissible states, and so forth. In the control architecture presented here, levels are more specific to the mobility and local navigation problem, and are first determined based on natural partitions for the roving task, i.e., geometrically, according to the relative scale of the rover to the terrain features. Further subdivision of levels corresponds to the intrinsic decomposition of legged locomotion into maneuvers, steps, and constituent motions. This difference in specification of the hierarchical levels is of a fundamental nature. For example, in the present architecture, a maneuver is simultaneously a "permissible state" and a "sequence of permissible states" (since a maneuver is a sequence of steps, which are permissible states at the next lowest level). Furthermore, a step is a partial ordering of constituent (potentially concurrent) motions, and therefore cannot be simply expressed as a sequence.

In contrast to Brooks' architecture[6], hierarchical decomposition here is in terms of levels of information abstraction as opposed to levels of competence. Examples of increasing levels of competence in Brooks' layered control system are:

Level 0: Avoid contact with objects,
Level 1: Wander aimlessly around without hitting things,
Level 2: "Explore" the world without seeing places in the distance and heading for them.

Whereas objects are higher-level entities in the current architecture, entailing a significant capability to deal with abstract concepts, in Brooks' architecture objects occur at the very lowest (0th) level. While level of competence and level of cognition are surely correlated, they are far from equivalent.

4. WALKING BEAM DESIGN CONCEPT

One of the vehicle concepts being considered by Martin Marietta as a candidate MRSR rover is the Walking Beam[4] design shown in Figure 7. The Walking Beam is a collapsible seven-legged vehicle that consists of two platforms joined along the central beam, each with its own set of legs. It propels itself by alternately moving one set of legs with respect to the other. Rotation of the outer T-beam tripod while the vehicle is supported by the inner four-legged platform provides vehicle steering. Translation is achieved by level, nearly frictionless rolling on a central beam. Foot placement is vertical; this minimizes soil work and vehicle slip, which are major sources of power consumption and odometer error, respectively, for rolling vehicles. Since the vertical and horizontal motions of the vehicle are decoupled, actuator conflict (a major source of parasitic loss in conventional walking vehicles) is also minimized.

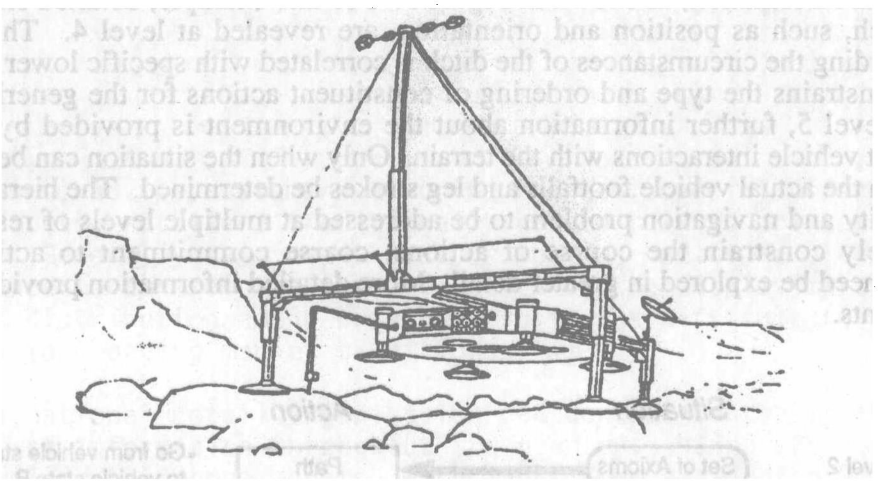

Figure 7. Walking Beam Concept.

5. MOBILITY AND NAVIGATION ACTIONS FOR THE WALKING BEAM

Hierarchical categories of legal operations for the Walking Beam are shown in Figure 8 and consist of the following actions:

- Level 2: Path Plan Specification - the ground track and associated vehicle states that the rover attempts to follow (every path plan consists of a sequence of maneuvers),
- Level 3: Maneuver Specification - general behaviors in response to generic situations encountered (each maneuver type consists of a distinct sequence of primitive stepping cycles),
- Level 4: Step Specification - the basic building block for driving decisions; each type of step is a distinct partial ordering of sensing, computation and mechanical motions,
- Level 5: Step Constituent Specification - characterization of the temporal, kinematic and information states for the sensing, computation and motion constituent actions that make up a step.

Path generation for a vehicle traverse specifies how the vehicle goes from an initial state (position, orientation, etc.) to a final state. Situations which can initiate a path planning or replanning activity include the receipt of new orders or data from Earth, current or impending failure of the current plan (e.g. significant differences between actual and expected state) or normal periodic updating of the plan in accordance with the vehicle concept of operations (e.g., generatation of a 30 m path plan after every 10 m path execution). A path consists a sequence of maneuvers.

A maneuver is a course of action in response to a mobility or navigation event. For example, the termination of a traverse is associated with a terminal positioning maneuver. Events are collective situations entailing the terrain environment, vehicle state, and rover tasks and constraints which suggest some decision-making action by the rover to optimize performance or ensure safety. Terrain events are the most obvious types of events, e.g., the event of encountering an obstacle elicits an obstacle-handling maneuver. Events and their associated maneuvers are abstract entities. Perception of an event is basically a recognition process that determines that a specific type of predetermined class of situations has been observed, for example, the detection of a ditch by the vehicle. For the degree of understanding possible at level 3, nothing more can be said about the object in question other than it is a ditch; its exact position, dimensions and physical properties are not determinant at this level. But just the fact that it is a ditch is sufficient to know that a generic ditch-crossing maneuver is appropriate, and should be incorporated into the path plan. Specification of the details of the ditch crossing maneuver requires additional information, as shown in Figure 9. For this example, detailed characteristics that describe the ditch, such as position and orientation, are revealed at level 4. This more detailed information regarding the circumstances of the ditch is correlated with specific lower level operations, which further constrains the type and ordering of constituent actions for the generic ditch-crossing maneuver. At level 5, further information about the environment is provided by high resolution sensing and direct vehicle interactions with the terrain. Only when the situation can be described at this level of detail can the actual vehicle footfalls and leg strokes be determined. The hierarchical approach allows the mobility and navigation problem to be addressed at multiple levels of resolution. Coarse situations coarsely constrain the course of actions; coarse commitment to action narrows the possibilities that need be explored in greater detail. More detailed information provides more specific action commitments.

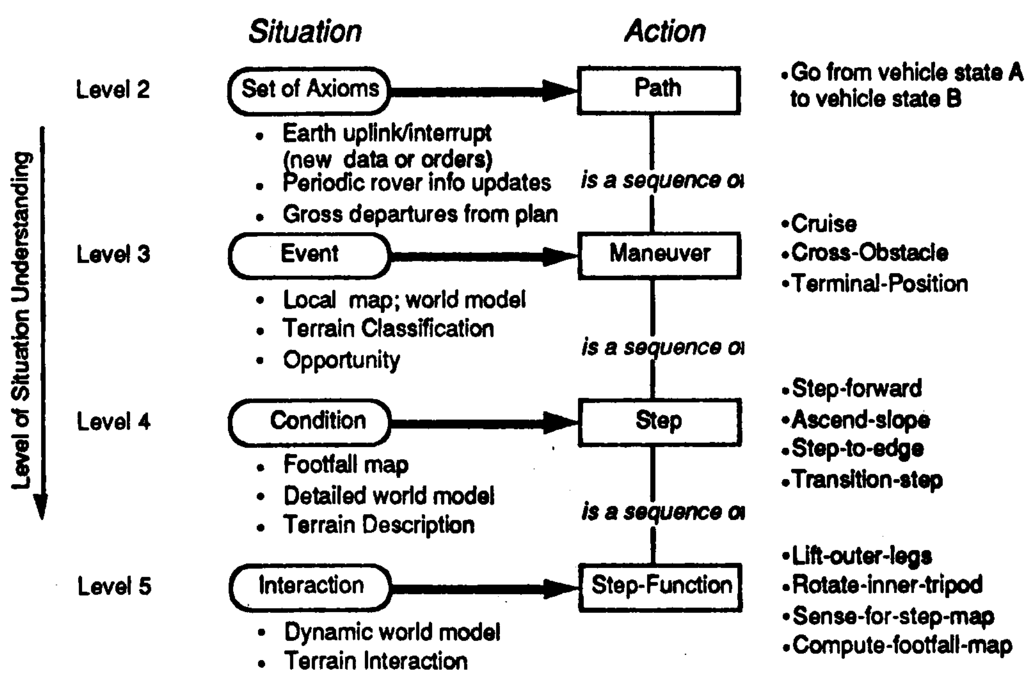

Figure 8. Simple Stimulus-Response Hierarchy.

Events can also be opportunities as well as problems. For example, if on closer inspection, an object initially perceived as a hazard is shown to be benign terrain, the update of the world map can trigger a replanning maneuver or a maneuver to seek Earth help. In either of these latter cases, the associated maneuver involves no vehicle motion (other than perhaps stopping). The term maneuver in the current context therefore denotes a more general course of action that simply moving the vehicle. Communicating with Earth, replanning, gathering panoramic or specialized sensory data, and waiting for suitable conditions (such as daylight or a fog to lift) are all considered maneuvers under this broader definition. An exhaustive classification of all events and their associated maneuvers is not only prohibitive but it is also counterproductive. Every possible combination of vehicle state,