COGNITIVE CONTROL OF AUTONOMOUS MOBILE ROBOTS: NESTED HIERARCHICAL INTELLIGENT MODULE

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On the Similarity Between Cognitive Controllers

An overview of the recent results in the area of Autonomous Control Systems for mobile robots suggests that different control systems show definite resemblance with each other: they have a hierarchy of knowledge-based decision-making units even when the system is equipped by a single actuator. It seems that all autonomous operations should be solved in such a similar (possibly, anthropomorphic) way. A concept of **hierarchical nested knowledge-based structure** is introduced in this paper which reflects the common properties of cognitive controllers, and an application of this concept is unfolded for a system of knowledge-based control of autonomous robots.

It is proven theoretically that nested hierarchies allow for an efficient knowledge organization as well as for correspondingly efficient knowledge processing. Theory of control oriented knowledge organization is being considered a part of a theory of **Autonomous Control Systems (ACS)** focused upon development of knowledge-based models of perception, memory, actuation, structures of algorithms, and design of systems for optimum motion of autonomous or semiautonomous systems. Theory of ACS implies that the similarities among the existing structures of autonomous robots (mostly, knowledge-based) reveal a number of inner mechanisms of goal oriented dealing with knowledge.

What Is Autonomous Control System?

Knowledge based ACS are defined as intelligent machines which should be able to operate in **completely or partially unknown environment** (or not yet recognized) with variable and/or uncertain traversability of the state space. This includes cases of obstacle strewn environment as well as other situations based on incomplete and/or intrinsically imprecise information. Autonomous Control Systems serve as a substitute for a human operator in the multiplicity of cases where **the danger** for a human operator is expected, and also in a number of cases where the **intelligent duties** of the system require higher performance than can be provided by a human operator. It is assumed that ACS participate in goal-oriented activities, and the problems to be solved allow for its structuring in subproblems, tasks, etc. In other words, ACS is a *Golem-system*.

The structure of a typical Autonomous Control System in very general terms can be represented as shown in Figure 1. This structure contains the closed loop of a controller (sensors, perception, knowledge base, control and actuation loop closed through the world), and an external connection via communication link which serves to assign and reassign a task, to receive the results of the reconnaissance, to start the required ACS operation, to abort the operation, to update the ACS , and also to provide communication of several ACS units working as a team. The following features are critical: **real time operation, redundancies, space and weight constraints**.

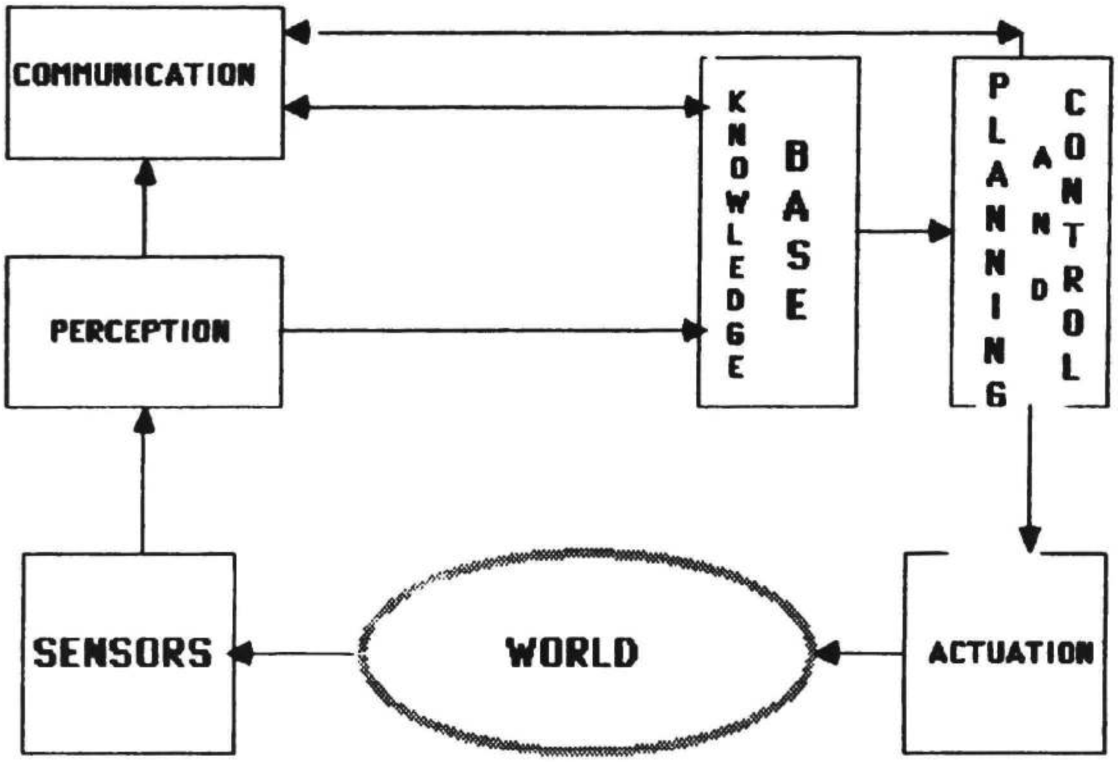

Figure 1. Structure of Autonomous Control System

Theory of ACS: Does It Exist?

Most of the virtual body of the theory of ACS control is implied by the results using "metaphorical" structures of cognition and incorporating the general results of the mathematical systems theory and theory of automata [M. ARBIB, 1969, 1972; R. E. KALMAN, 1969]. Some of the more recent papers help to refine the backgroung for the possible practical application [A.G. BARTO, 1981; J.J. HOPFIELD, 1985]. However, the problem of engineering design and manufacturing of ACS requires something more than a number of important general theoretical premises. The system of ACS turns out to combine a cluster of interrelated problems that must be solved only as a result of an effort with simultaneous and consistent consideration of topics treated usually in different scientific languages.

One important thing captures our attention in a variety of ACS realizations: they all are built in a hierarchical way. Structures of hierarchical intelligent control [G.SARIDIS, 1977, 1983] are potentially the proper tools for solving problems of control oriented manipulation with knowledge. Certainly, they should be given at least a rudimentary capability of performing **cognitive operations** which is usually done by various techniques of artificial intelligence, self-organizing automata, and neural networks. Part of these cognitive operations is learning which should change the quantitative evaluators in the list of rules (relations) as well as introduce new rules.

The model of dealing with cognitive operations in a form of perceptron-like fuzzy-state automaton was first introduced to simulate activities of human cerebellum (J.S. ALBUS, 1975), and then extended for application in a multiplicity of technological hierarchical structures (J.S. ALBUS, 1979, 1985). Similar methodologies are emloyed in a number of knowledge-based controllers (E.H. MAMDANI, S. ASSILIAN, M. BRAAE, D>A> RUTHERFORD, G.A. CARTER, H.R. van NAUTA LEMKE, J.J. OSTERGAARD, etc.).

Knowledge in Autonomous Systems

Knowledge Bases are usually considered as a source of well-formed formulas for man-machine decision-support systems of different kinds. Differential equations are not the only way of convenient world representation, and in the automata theory, we have a broadly developed basis for building various systems of control. Automata formalisms appear in a natural way, when the struggle with nonlinearities, coupling, and cumbersome computations brings us to the idea of **table** (look-up).

Tables can be considered as ordered lists of clauses, (certainly, logic is presumed to be multivalued with fuzzy and/or probabilistic assigning of quantitative data). Generalization upon tables generate lists of logical (linguistical) rules. Goal oriented set of generalizations upon the lists of logical (linguistical) rules, leads to the hierarchical organization of information ("knowledge"). Goal oriented hierarchies created in this way, satisfy the following principle: *at a given level, the results of generalization (classes) serve as primitives for the above level.* Then each level of the hierarchy has its own classes and primitives; thus, it has its own vocabulary, and the algorithms assigned upon this vocabulary can be adjusted to the properties of the objects represented by the vocabulary. It is assumed that *metarules* providing the operations mentioned above, are part of the system.

It is proven that the ϵ-entropy of the knowledge organization, can be reduced using proper selection of **resolution reduction factor,** during the process of generalization. Several different knowledge hierarchies are shown to affect the operation of ACS: hierarchy of knowledge represented in the mechanical assembly, hierarchy of knowledge represented in the motion control system, in the system of sensors, and finally, in the **architecture of the knowledge processing system** *per se* (see Figure 2,a).

Each of the cones represents the resolutional hierarchies of knowledge at different levels of consideration. The domains covered by each of the "cones" communicate enabling translation among the domains. In Figure 2,b the structure of the **general knowledge** cone is shown for three levels of hierarchy. Finally, in Figure 2,c the consecutive decomposition is shown for a map of the world. Each of the consecutive images is obtained as a result of "**zooming**" procedure for the **area of attention**.

Hierarchical Nested Controller (HNC)

The ACS hierarchy is usually produced by the physical existence of a multiplicity of actuators (and/or sensors) as well as by the structure of problem, its decomposition in tasks. Then, the branching of hierarchical tree follows if the required operation (actuation) can be associated with a single

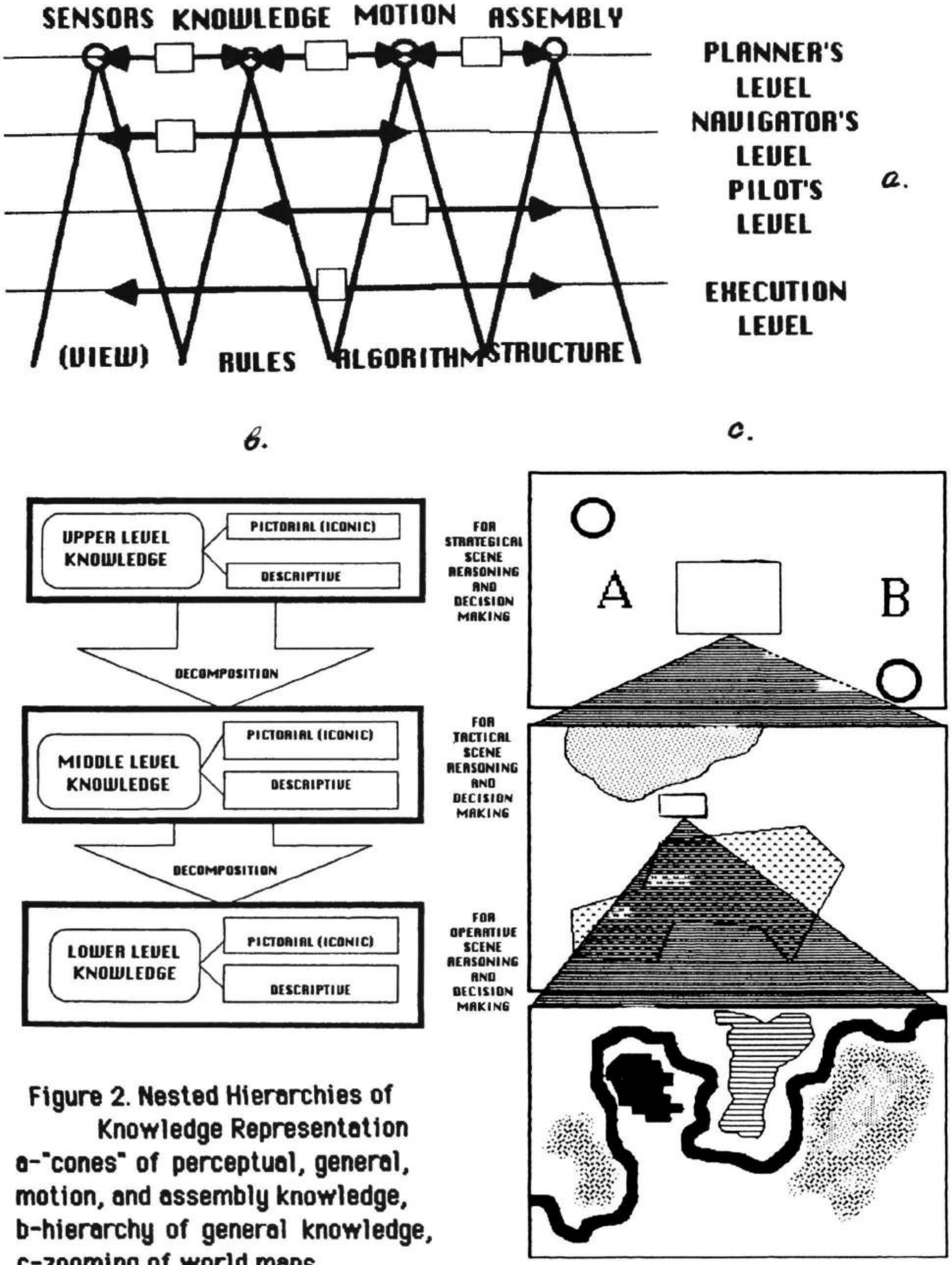

Figure 2. Nested Hierarchies of Knowledge Representation
a-"cones" of perceptual, general, motion, and assembly knowledge,
b-hierarchy of general knowledge,
c-zooming of world maps.

task decomposable in parts and those parts should be performed by a set of different actuators. **However, the hierarchy is retained even when only one actuator is being considered**. This would be a hierarchy of nested decision making processes over a nested hierarchy of world representation where each of the levels can be characterized exhaustively by the value of **resolution of knowledge representation**.

Hierarchical decision making process allows for using the limited computer power at each level of such hierarchy with no branching efficiently by consecutive zooming procedures.This hierarchical system of representation employs Minsky's "frames" or Samet's "quad-trees" in a "natural" way.. In this case, the tree hierarchy of intelligent control converts into a **hierarchical nested controller (HNC)**.

If HNC is acting under the above mentioned constraints the process of control allows for decoupling in parts dealing separately with information of different degree of resolution (easily interpreted as certainty, belief, etc. This means that the degree of "fuzziness" is different at different levels of the hierarchy, and in the nested hierarchy of the fuzzy-state automata **each automaton of the lower level (automaton-child) is enclosed in the corresponding parent-automaton**, and serves for clarification of its uncertainties.

A nested hierarchy of knowledge which is organized according to the degree of certainty and belief, implies a nested hierarchy of decision-making processes which in fact, leads to a similar nested hierarchical structure of **PLANNER-NAVIGATOR-PILOT** currently employed in some versions of mobile autonomous robots. ACS functioning depends upon a subset of cognitive operations in HNC associated with **motion planning, navigation, and control for autonomous mobile robots**. Thus, Figure 1 can be modified, and the refined structure of the system which reflects the HNC operation, is shown in Figure 3.

Nested Hierarchy of Knowledge in ACS

Clearly, the functional subsystems of ACS: "Perception", "Knowledge Base", and"Planning-Control" are intrinsically interlaced, and Figure 3 shows that they can be considered as an entity ("intelligent module"). This entity is built upon two interrelated knowledge bases: one, carrying the entity-relationships (ER) structure of the world, and another, defining operations upon this structure. The operations are determined by the actual character of the primitives at a given level of consideration. These two interwoven knowledge bases constitute the background for the ACS operation.

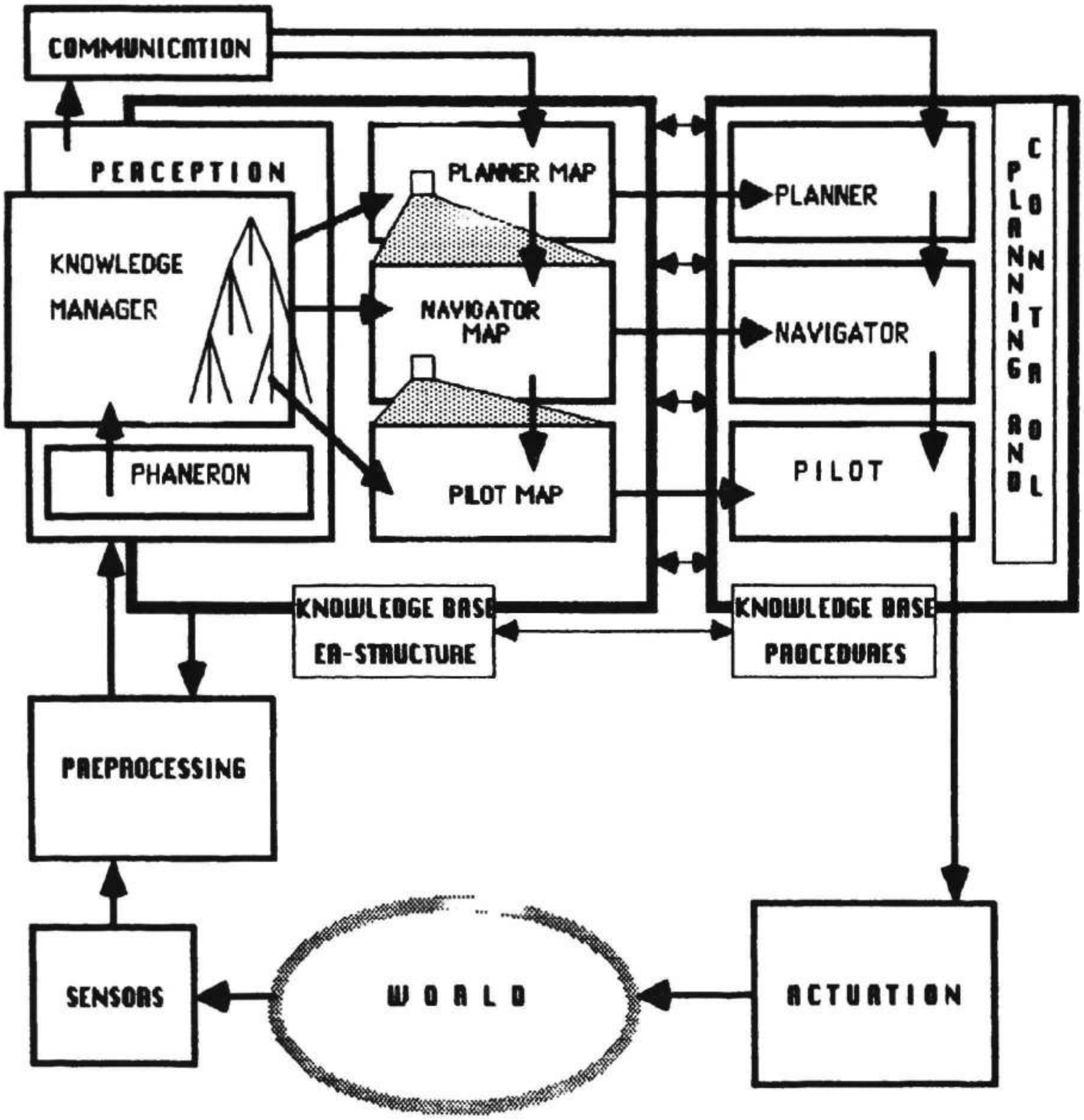

Figure 3. Refined ACS structure: HNC operation is illustrated

Perception Stratified by Resolution

Knowledge acquisition is understood as a **two-step process** consisting of **information acquisition** (which is done by sensors), and **information organization** (which in fact, transforms the raw information into knowledge). First, sensors deliver **phaneron** to the knowledge manager. (The term "phaneron" was introduced by C.S. Pierce for the totality of information which can be called **phenomenal world**). Phaneron is not structured at the moment of arrival, it should be recognized, identified within some ER-structure which might not yet been created. These processes are broadly discussed in literature, and the importance of such phenomena as "**attention**", and "**resolution**" in the process of knowledge acquisition was emphasized many times in literature (R. Bajcsy, M. Levine, A. Hanson, E. Riseman, etc.).

The result of this first step of knowledge acquisition (a **snapshot of the world),** contains information part of which can be different in the next snapshot, and part won't change (e.g. about relations among objects and/or their properties). Thus, the identification can be done only in the context, i.e. in constant interaction with knowledge base. This affects the set of preprocessing procedures which are being separated from the rest of the intelligent module primarily because of successful experience of modular manufacturing of the computer vision systems systems. Simultaneously with the process of finding phaneron structure (or image interpretation) the problem of proper allocation of the information contained within phaneron should be done. Thus, the system of nested hierarchy of Planner-Navigator-Pilot maps is being created.

Knowledge Representation Stratified by Resolution

Separation in levels appeared to be a natural phenomenon linked with the properties of **attention**, and its intrinsical links with the process of **generalization.** In fact, generalization is required to provide the efficiency of computing resources use and allocation, and attention is one of its tools. Thus, the new class labels which are created by the process of generalization, are being considered as new primitives of the upper level of world representation. This rule: **the class labels of the lower level are considered as primitives for the higher level,** is one of the laws of the mechanism of nested hierarchy.

Knowledge represented by ACS contains at least two parts: thesaurus and context. Thesaurus is maintained independently of particular operation to be performed, and it constitutes the ASS "wisdom", "education", and "experience". Context is determined by the task within a domain of thesaurus, and can be considered as a "map" of the world in which the operation must be designated together with the list of rules pertaining to this map. Map of the world is extracted from the series of snapshots.

Knowledge in the form of "planner's map" should be maintained for a long time due to the "slow rhythm" of this level. Changes in the upper level map are not frequent. "Navigator's map" is to be regularly updated but it can be maintained as a part of "planner's map". Pilot may or may not need a map maintained as a part of "Navigator's map". Actually, from our first experience of dealing with ACS we found that intelligent module cannot afford maintenance of the pilot map (the lowest level of world representation), and therefore all processes related to the real time operation have **ephemeral structure** with a number of logical filters determining whether this ephemeral information contains anything to be included in the long term memory.

Maps that have emerged on the surface of the ER-structure as a working representation of phaneron, imply corresponding procedures of motion planning and control.

Planning/Control Stratified by Resolution

Planning is traditionally considered to be a process which is performed separately from the process of control. This is acceptable for the vast multiplicity of systems where planning can be performed off-line, and the process of control can be initiated given a set of highly generalized **units of knowledge** together with a number of **unchangeable goals**. By lowering the level of generalization and keeping the certainty and belief in
the required limits of the level **resolution**, we can build in a hierarchy of nested planning processes. In this hierarchy, the desirable trajectory determined at the higher level arrives to the lower level as a **fuzzy stripe** (FS). The new planning is being done within FS at a higher resolution.

This decoupling of the decision-making upper levels (or *off-line stages*) from the lower levels of decision-making and immediate performance (or *on-line stages*) is probably the most characteristical property for telling the planning stages from the control stages of operation as well as distinguishing the corresponding subsystems or any device where **constant human involvement** is presumed. This decoupling does not take place in ACS: planning and control are the inseparable parts of the unified HNC. The levels of planning and control are connected together by an intermediate level of decision making dealing with processes which have to use knowledge at a definite level of generalization and yet after processes of updating are completed.

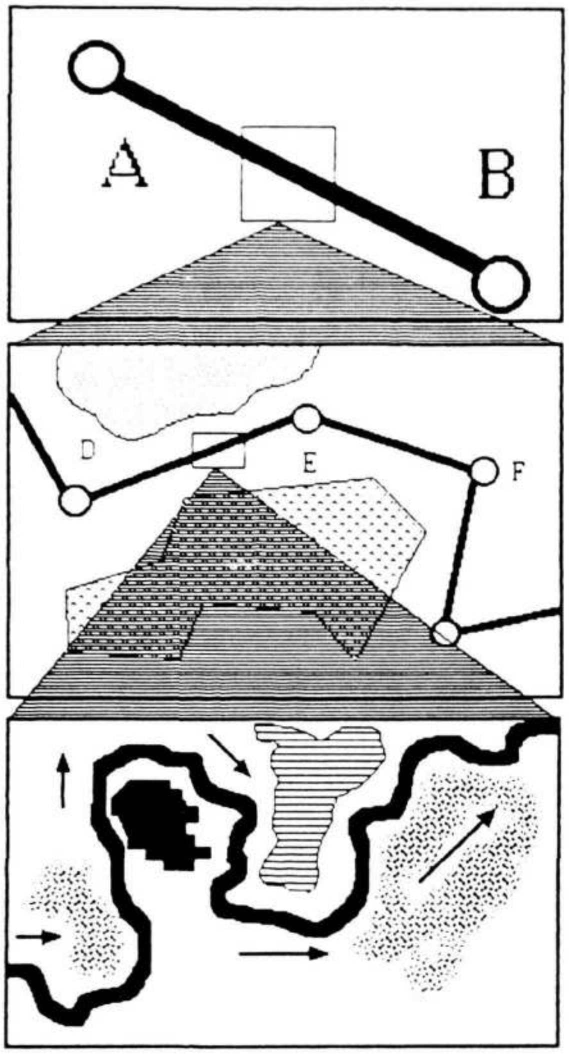

Figure 4. Planning as a nested hierarchical process

This means that at this intermediate level, the results of the ongoing motion affect the results of generalization (sinse the system of "Perception" initiates processes of information updating). We name planning processes **navigation** *per se* at the level of "Planning-control" subsystem where the results of real-time updating are becoming crucial for the results of planning. In Figure 4, three consecutive nested operations of planning are performed at three resolutional levels of the system. One can see that at the level of the least resolution, the plan is visualized as a straighr line AB. After zooming a segment of this line into higher resolution, new information is obtained, the straight line is being substituted by another plan: DEF. The next zooming discloses even more details about the environment. The actual motion among small obstacles is shown in the third map. So, these three plans show different paths, the direction of motion seems to be different. And yet, all of them are correct plans after being related to the resolution of a particular level.

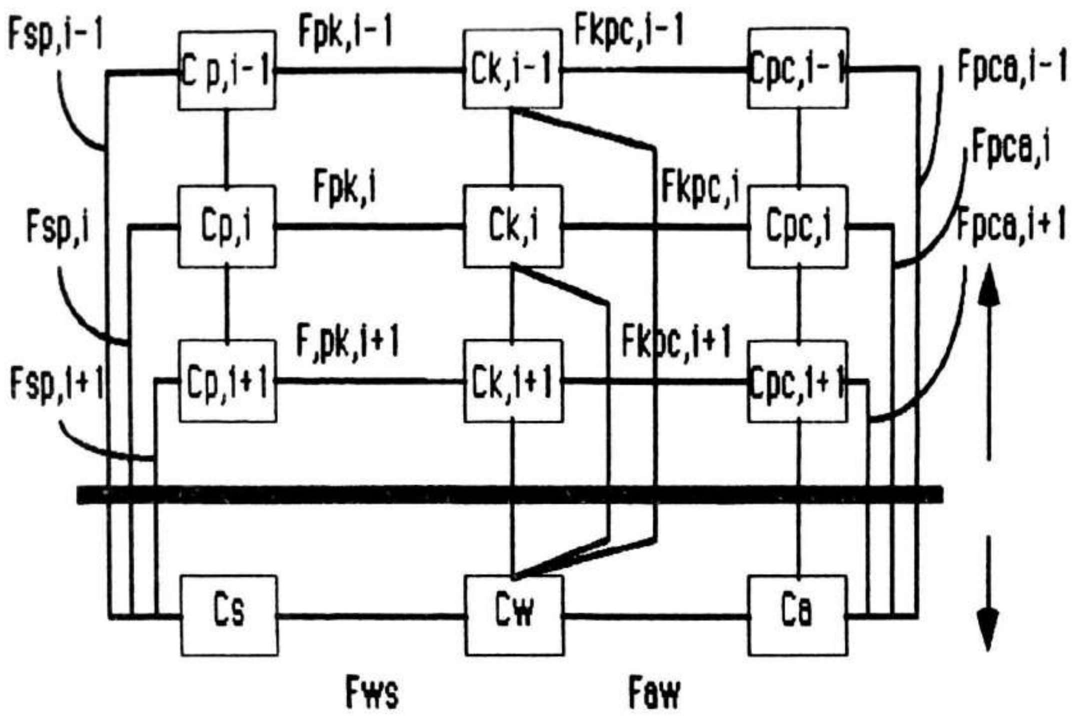

Figure 5 Category-theoretical Representation of ACS

Nested hierarchy of perception does not require having any hierarchy of sensors although does not preclude any acceptable hardware solution. Nested hierarchy at the stage of preprocessing is being viewed as a result of sequential **zooming** operation, or in other words operation of the **focusing of attention**. In ACS zooming must be based upon focusing of attention otherwise, the constraint of the limited computing power would not be satisfied. (One can see that this concept can be interpreted within the framework of existing theories of image organization and interpretation, see A. HANSON, E. RISEMAN, 1978).

Nested Hierarchical Production System

All of the planning-control levels of the mechanism of **knowledge-based navigation** interact vertically via recursion of the **algorithms of sequential production** providing sequential refinement top-down, and correctional replanning bottom-up. Functioning of the hierarchical production systems of perception, and planning-control, is supported by vertical interaction of levels in the "Knowledge Base" via aggregation and decomposition based upon preassigned values of resolution per level. So, the thesaurus as well as context, exist as a result of internal processes of self-organization within the body of knowledge.

On the contrary, the two couple of subsystems: "Perception-Knowledge Base" and "Knowledge Base-Planning/Control" (shown in Figures 1 and 3) are being viewed in our theory as **vertical nested knowledge processing hierarchies with horizontal interaction per level**. Indeed, all new knowledge acquired should be organized, the list of primitives in operation must be verified and updated. This procedure is being done at a horizontal level as well as excercising the algorithms of control. In the latter case, the map of the world as well as the list of rules to deal with this map are becoming an object of heuristic discretization and search.

Category-theoretical description of ACS

Considering subsystems as **categories C**, and the interaction among them as **functors F**, the commutative diagram can be shown as follows (indices mean: s-sensing, p-perception, k-knowledge, pc-planning/control, a-actuation, w-world) as shown in Figure 3. (Feedbacks are not shown: boxes are connected by "functors" which characterize the structure conservation in a set of mappings of interest). The bold horizontal line separates two major different parts of the system: what is below, is a world of real objects, and what is above the bold line, is the world of information processing.

All of the "boxes" in Figure 3 are fuzzy-state automata. They are easily and adequately described in terms of the automata theory, provide consistency of the descriptions, computer representations, control operation, and they are taylored for dealing with knowledge processing. Then, the search can be done by combining A* and dynamic programming, discretization of the space is being determined by the level of resolution, and the rules which are formulated within the given context.

Knowledge-based Optimum Control of ACS

In this area, the methodology of knowledge engineering can give substantial benefits. The problem of motion planning was given attention in the literature on AI and robotics. However, in a pure analytical domain problems of **optimum planning** as well as **optimum control** until now do not have applicable solutions. Motion planning is frequently understood in the context of **"solvability" of the problems of positioning or moving** the object rather than in the context of finding the desirable trajectory of motion. Nevertheless one cannot argue that the real problem of concern is finding the location and/or trajectory of motion which provides a desired value of some "goodness" measure (e.g. the value of some cost-function). These features of the problem, constitute a good "bridge" for interference of knowledge engineering methodology.

The emphasis of the well known concept of the "configuration space approach", is done upon techniques of constructing the **admissible** swept volume but no **optimality** is considered, and certainly, no dynamics of the motion is discussed. Most of the algorithms based upon the theories mentioned above, are oriented toward **off-line operation**, they require considerable time and constant human involvement. Finally, all of the existing works presume complete knowledge of the environment, and operate in a structured world. No result is known contemplating planning of motion in unstructured situation. In the meantime, this situation is a typical one for a hierarchical system of **knowledge-based autonomous control.**

Considering the problem of motion planning as a pure geometric issue, can be understood given complexity of this problem, and the mathematical elegance of solutions it generates. We would like to express here our appreciation of the results containing the advancements in using configuration space (T. LOZANO-PEREZ, M.A. WESLEY, W. RED, H.V. TRUONG-CAO. A.A. PETROV, T.M. SIROTA), in finding the minimum distance path under geometrical constraints (J.Y.S. LUH, C.S. LIN, L.A. LOEFF, A.H. SONI, S.M. UDUPA, C.E. CAMPBELL), upon the network (G. GIRALT, R. SOBEK, R. CHATILA, V.A. MALYSHEV), using the Voronoi diagrams for motion planning with and with no retraction (R.A. BROOKS, C.K. YAP) as well as introduction and the treatment of such problems as "moving the ladder", "moving the piano", and so on (C.K. YAP). Various methods of minimum path construction have been applied based upon determining the "potential field" surrounding the obstacles (O. KHATIB), global flow analysis using Gauss-Jordan elimination (R.E. TARJAN), applicable when the full knowledge of the world is presumed to be given. An interesting example of using neural networks for optimization of motion (J.J. HOPFIELD, D.W. TANK, 1985), is promising within the aspect of this paper.

The following comment should be taken in account: the above mentioned works reflect a paradigm of **off-line static planning of motion trajectory in a cluttered limited well known** space. Clearly, this is only a part of the whole problem- an important one but just a part. As soon as the **on-line real-time** planning is required, as soon as **dynamics** is involved, as soon as the "plant" is **complex and hierarchical** one, and the world is **not uniform** and **not well known**, finally, as soon as the computer power turns out to be limited (as happens in all autonomous systems) - then the old premises are not working anymore.

Experience of Simulation and Testing

Based upon this approach, a nested hierarchical intelligent module has been developed for knowledge-based control of an autonomous mobile robot. The module was simulated, and the processes ofknowledge acquisition, organization and knowledge-based planning-control have been analyzed in a variety of situations including a number of terrains including flat and 2 1/2 D ones (D. GAW, A. MEYSTEL, 1986), obstacle strewn environment (A. MEYSTEL, A. GUEZ, G. HILLEL, 1986), and different cost-functions for optimum control. Simulation of nested hierarchical planning is illustrated in Figure 6. One can see that after development of the upper level plan (**"go straight from initial position to goal"**), next level (Navigator) changes the plan upon updating map by obstacles information. Middle-level plan is developed in presumption that there is an exit on the right. The lowest level, Pilot visualizes the obstacle, and the motion is again replanned and corrected.

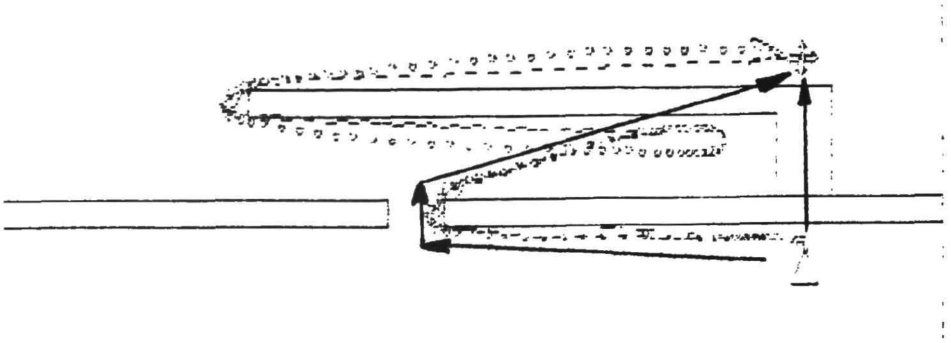

Figure 6. Example of NHC simulation

The processes of dynamic navigation have been analyzed (A. GUEZ, A. MEYSTEL, 1985). The results have confirmed that nested structure is applicable for goal oriented motion refinement of minimum time dynamic system. The software package corrected after computer simulation, is being verified by testing an indoor mobile autonomous robot (with ultrasonic "vision"). Indoor testing has confirmed the NHC analysis. New advanced algorithms of Piloting has been developed.

The outdoor system is being developed for operating upon terrain 5x5 sq. ml. Navigator's focus of attention is 1500x1500 sq.ft. Focus of attention at the Pilot level is 200x200 sq. ft. The principle of Nested Hierarchical Control is represented consistently in all of the subsystems. In order to provide the outdoor test of the the system, a vehicle is being

outdoor test of the the system, a vehicle is being

manufactured with three levels of vision (with a laser-scanner, with a CCD camera, and with ultrasonic sensors). NHC enable development of a new principle of Vision at the Pilot Level using segmentation with no edge detection.

Computer Architectures

Theory of hierarchical nested control not only generates the conceptual knowledge acquisition and processing oriented architectures of cognitive modules for autonomous mobile robots, but also suggests number of preferable computer architectures as well as techniques of dealing with the problem of assemblying the system from existing architectures. These architectures are implicitly described in a part of Figure 3 above the bold line.

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