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TECHNIQUES AND POTENTIAL CAPABILITIES OF MULTI-RESOLUTIONAL INFORMATION (KNOWLEDGE) PROCESSING

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Abstract

A concept of nested hierarchical (multi-resolutional, pyramidal) information (knowledge) processing is introduced for a variety of systems including data and/or knowledge bases, vision , control, and manufacturing systems, industrial automated robots, and (self-programmed) autonomous intelligent machines. A set of practical recommendations is presented using a case study of a multiresolutional object representation. It is demonstrated in the paper, that any intelligent module transforms (sometimes, irreversibly) the knowledge it deals with, and this transformation affects the subsequent computation processes, e.g. those of decision and control. Several types of knowledge transformation are reviewed. Definite conditions are analyzed in this paper, satisfaction of which is required for organization and processing of redundant information (knowledge) in the multi-resolutional systems. Providing a definite degree of redundancy is one of these conditions.

***Key Words:** Abstraction, Generalization, Image Analysis, Interpretation, Knowledge, Multigrid Relaxation, Multiresolutional, Pyramidal, Redundancy, Representation.*

I. Introduction

A concept of nested hierarchical (*multi-resolutional*, pyramidal) information (*knowledge*) *processing* (MRKP) is becoming increasingly important in the area of intelligent machines including robotics, computer vision, and knowledge-based material processing. *Multiresolutional Knowledge Representation is defined as the union of all monoresolutional representations.* Monoresolutional representation is understood as a representation of the particular set of reality [1] at a resolution commensurable with the subset of required measurements and activities.

The main idea of this concept is that the applicable model of a system cannot be built unless this system is considered simultaneously at several levels of resolution [2]. Resolution is defined as a minimum volume of the state space that is distinguishable within a particular system of representation. This minimum volume is called *tessella* (in Latin - minimal element of a mosaic), and organization (discretization, quantization) of the state space is called *tesselatrion* if a particular size of tessella is being used efficiently as an element for building all descriptions of interest.

[1] Set of interest

[2] Thus, MKR is not equivalent to the "syntactic" representation known in the theory of pattern recognition. The latter does not require that each level of the syntactic graph to be necessarily a complete representation of the set of interest. However, the methods of dealing with these representations are similar. This problem should be discussed separately.

Many characteristics (properties, variables) make sense only at a particular level of resolution, and do not need to be reflected at a higher or lower resolutions. In the meantime most of the existing control problems cannot be solved only within one resolution level. Thus, a concurrent consideration of the system at several resolution levels is required, and the redundant representation is justified in which the "same" thing is represented several times with different resolution. Utilization of MRKP is discussed in [1], and a brief survey of literature on multiresolutional models of knowledge organization is given in Section 2.

A notion of **multiresolutional knowledge representation (MKR)** is introduced for a variety of systems including data and/or knowledge bases, vision , control, and manufacturing systems, industrial automated robots, and (self-programmed) autonomous intelligent machines. Most of these applications are actually, or presumably utilizing **intelligent modules** with decision making capabilities, (or human operators performing similar functions). The structure of intelligent module is described in [1], (this is a system which exercises intelligent control similar to what in AI literature is called sometimes an *intelligent agent*). MKR is derived directly from the entity-relational representation of a system. This representation is using the following postulates of representation:

Postulate 1. Any representation is derived from a verbal [3] description [4].
Postulate 2.Any verbal description transmits information about labels (words) that can be interpreted within some global thesaurus.
Postulate 3. Relations among the labels can be determined from the same description or from the set of related descriptions (context [5]).
Postulate 4. Relations among the labels can be numerically evaluated in the scale generated by a metric meaningful for considering a particular label.
Postulate 5. The set of interest at a particular resolution level has a multiplicity of corresponding sets at all other levels of higher as well as lower resolution; each of these sets represents a concrete set of reality with resolution pertained to the set; only all of them together adequately (completely) represent of the concrete set of reality.

The first three postulates are establishing a graph representation for the system of interest. This graph includes all levels of resolution since it contains not only the systems represented but also their components, and components of their components, and so on. The last postulate presumes that the classes can be recognized among the multiplicity of labels, of those **commensurable** labels,

[3] The word "verbal" is used in a very general sense. Of course, it means "expressed in words". Obviously, it includes any process of discretization when the signal is assigned a discrete number for further utilization in the algorithm where the number is used as a value for the signal (so, the signal, or in general, a variable is considered to be a *word with a value*). However, it includes also any process with no discretization since in the analogous systems we can use a loop in which a variable (a word with a value) is operating with no discretization required.

[4] I.e. even we have a pictorial description either we transform it into words before using it, or it by itself is a result of transforming the verbal description into a pictorial illustration. Also, the word description is related not to a particular description which almost definitely is always incomplete, but rather to a **representative set of verbal descriptions** which is considered to be representative by the experts in this area. This set can include scientific papers, articles from trade magazines, technical reports of industrial companies, and/or universities, as well as interviews with the experts.

[5] Context is presumed even it the verbal descriptions are only implicit ones and exist as a potential set of descriptions within the experience of experts. (Another problem is that the descriptions generated by these experts are not necessarily conducive to the transfer of objective information about their experience).

i.e. belonging to the same space of consideration. The subset of commensurable words we will call a **scope**. Figure 1 illustrates the entity-relational graph ("a"), the ability to view this graph in a variety of scopes (e.g. I-"function", II-"perception", III-control [6]"), and the ability to redraw it in such a way as to reflect this classification into this set of scopes ("b").

One can see that the structure can be visualized as a set of the interrelated scope graphs $\cup G_i$, $\cup G_i \mathbf{R} G_j$; i,j=I,II,III, i≠j, where Rij is a relation among the elements of the graphs. Each of the scope graphs has a set of vertical (hierarchical) connections of the resolution levels and this set of connections is called a *hierarchy of the scope*. Within each level of resolution an entity-relational graph (*tessellatum*[7]) exists which represents all entities and relations among them at a particular resolution (or accuracy which is characterized by a minimum cell of distinguishability (*tessella*). There are no hierarchies within a tessellatum: all entities that can be partitioned are partitioned and their parts belong as entities to a lower level tessellatum. All tessellata belong to a particular hierarchy and are being considered together with it:

$$G_i = \bigcup_{i\kappa} T_i^{\kappa} \mathbf{R} T_i^{\kappa+1}$$, k=1,...n, i=I, II, III (k is a number of resolution levels).

Each of the is unifying the set of inclusions for the tessellata

$$G_i = \bigcup (T_i^{\kappa} \supset_g T_i^{\kappa+1} \supset_g T_i^{\kappa+1} \supset_g \ldots \supset_g T_i^{\kappa+1})$$

where the inclusions are meant to represent the relations $\mathbf{R}$. These relations are of a special meaning: they reflect the fact that the entities and relations of the lower resolution levels can be obtained from the corresponding entities and relations of the higher resolution level via mechanism of generalization (or abstraction). Or, in other words: any tessellatum of the higher resolution level can be transformed into the tessellatum of the lower level via mechanism of *generalization (abstraction)*. This is why these inclusions have an index "g": it reflects that a special set of rules is presumed which provides this inclusion generating transformation of generalization (abstraction).

A set of all hierarchies with all tessellata related to each of the hierarchies forms a *heterostructure* (see **D-structure** in [2]).

A number of laws of multi-resolutional information (knowledge) organization and processing, enable us to deal with the subsystem of information (knowledge) independently from the associated subsystem of decision making the latter must be taken in account at the stage of designing the algorithms of information (knowledge) processing. In this paper we will focus only on the general matters which are important for the whole variety of methods of Multiresolutional Knowledge Processing (MRKP). This variety is surveyed in Section 2. Section 3 analyses a Case of MKR. Techniques of MRKP are discussed in Section 4. Finally the potential capabilities of MKR for MRKP are described in Section 5.

2. Overview of the Situation in the Area of MRKP

MKR and associated techniques of MRKP was rapidly developing during past two decades from three different views: hardware MKR, visual images MKR, and algorithms MKR (with fuzzy boundaries). Firstly, it has been realized that using effectively multilevel, multilanguage structure of

[6] These three types of scope are typical for making theories about many objects of external world because they actually exhaust the areas of interest and application.

[7] tessellatum- a mosaic floor composed of a multiplicity of minimal elements or tessella (from Latin).

a computer is possible only if this multilevel structure is explicitly, consciously associated with the multilevel (multiresolutional) organization of the World constructed by methods of aggregation (generalization, abstraction) and decomposition (instantiation). This became clear in CAD/CAM area, and a number of multilevel (multiresolutional) hardware descriptions appeared as well as methods of reasoning about World [3,4]. This area is linked with the problem of partitioning multiprocessor systems in order to achieve maximum of efficiency. Proper distribution of resolution among subsystems should provide the bast utilization of equipment [1,5].

Another MKR problem adjacent to the problem of hardware partitioning was the following: how to partition something that has not been previously assembled, (e.g. partitioning of a curve) [6]. It was determined that the following factors must be taken in account: digitization and/or resolution of representation on hand, existence of multiple "views", and the set of attributes utilizable for describing the object to be partitioned. Linkage of all these approaches is undeniable to the "frame approach" from AI, and aggregation/decomposition methodologies of the earlier scientists belonging to the school of thought of General Systems Theory (e.g. see [7]). A method of multiresolutional curve representation is presented in [8] which is a good illustration of the definition of the MKR, and of the *generalization* as a major technique which transforms the representation given at a higher level of resolution into the lower level of resolution creating a hierarchy of generalizations (or abstractions).

Pyramid theories of image processing and interpretation have been promulgated during the last two decades in a multiplicity of well known books and papers by L. Uhr, E. Riseman, A. Hansen, S. Tanimoto, T.Pavlidis, M.Levine, R.Bajcsy, P.Burt, A.Rosenfeld [9-14]. The idea of generalization of information from level to level is presented and developed in all of their papers, and a variety of methods is proposed for solving practical problems under these conditions. Most of them are boiling down to decomposition of entities of the upper level into the set of entities of the lower level in such a way as to have the whole level given at a definite particular resolution consistent with the context determined by the focus of attention at this level as illustrated in this sequence:

level of resolution ⇒ detail (tessella) ⇒ focus of attention ⇒ context ⇒ level of resolution

Interestingly enough, the well known quadtree structure [15] is not a multiresolutional structure in a sense that the accuracy of representation is the same at each level: the highest available accuracy of the level with the highest resolution (the lowest level of consideration).Only recently, there was an attempt to fuzzify the upper levels images when the problem of planning was attempted using quadtree as a MKR system [16]. Truly MKR approach with using all tessellata for planning was successfully employed in [33].

Partitioning driven by a linguistic description leads to MRKs which are instrumental in shape description. It turned out that the set of hierarchical connections (those of G_i type) forms a "skeleton" that can be used as a good enough "syntactic" [8] representation of various complicated shapes [18,19]. This phenomenon seems to have explanations within the principles of human perceptions reflected in the biological structure of vision system. This view was reflected in the multiresolutional model of the visual receptive fields [20]. Multiresolutional representation turned out to be useful also for image segmentation and to region matching [21, 22].

MRKP is kindred to the fractal methodology of world representation [23]. Multiple-scale based approach to image representation and analysis [24] together with fractal-based techniques is actually

[8] The problem should be addressed separately of reconciling the multiresolutional approach with its MRK systems with the well known syntactic methods of pattern description and pattern recognition (for example, like in [17]). The conventional syntactic representation and the representation (like in [17]) and MRK should not be confused.

application of the set of ideas characteristical for MKR. Here we are dealing with *simultaneous representation of all images at all resolutions* when the mechanism of generalization (or abstraction) is imposed upon the system by an external mathematical model.

Finally, the last group of MRKP results is related to the multiresolutional algorithms. Somewhat interlaced with the fractal methodology are the algorithms of continued fractions [25,26]. Multiresolutional relaxation algorithms have been recommended for efficient dealing with texture [27]. A consistent and complete overview of the multigrid relaxation algorithms for image processing can be found in [28].

3. A Case Study: Multiresolutional Representation of a Chair

Chair is a tempting example for illustrating the techniques of MRKP. Many researchers were choosing this object even in the area of multiresolutional information processing (F. Mokhtarian, R. Bajcsy, et al). In Figures 1-10 some of the illustrative material is presented. More detailed description of operations is given in [32].

4. Discussion of the Techniques of MRKP

As one can see from Figure 1, and the illustrating case, the core of operation of the intelligent module does not differ from the process of the **automated theory generation (ATG)**. The latter was first tackled in [29] and then was furtherly developed in [30] and other works. It is important to emphasize that any **process of representation is based upon theory generation**. Like in ATG, the subsystem of representation is supposed to synthesize a consistent system of tessellata constructed at different resolutions and transformable one into another. This synthesis can be performed in a different way depending on initial problem specifications. We give two examples a) for the case of "well known systems"[9] (i.e. knowledge is available if needed and all possible interpretations can be found), and b) for the case of a system with high resolution information available[10].

Case 1. "Well Known Systems"

- Step 1: present the description of a system including its function, its component, and its operation,
- Step 2: explain the meaning of the components, and the relations among them (ER graph),
- Step 3: perform steps 1 and 2 for the components of the system [11], and continue this down to the *meaningful* high resolution level,
- Step 4: determine (discover?) generalizations within the results of Steps 1 through 3 activities, which can simplify understanding, memorization, utilization, computation, and so on, of the system and its components. These generalizations can be in the form of rule tables, mathematical formulas, geometrical analogies, computational algorithms, and any another form applicable in the domain of interest.

Case 2. Systems With High Resolution Information Available

- Step 1: present the expected description of a system including its expected function, its expected component, and its assumed operation,
- Step 2: prepare the possible structure of interpretation for the components, and the relations among them (ER graph) at all meaningful resolution levels,
- Step 3: perform steps 1 and 2 for the components of the system within the expected tessellata, and continue this down to the *given* high resolution level,
- Step 4: determine (discover?) generalizations applicable within the results of Steps 1 through 3

[9] This case can be identified with those known in the CAD/CAM, FMS, etc.

[10] Applicable in computer vision systems.

[11] The system is presumed to allow consecutive decomposition ("consecutively decomposable system").

activities[12].

- Step 5. Apply the generalization required to each tessellatum bottom up and verify consistency of the representation.

Even in the case of image processing, generalizations are not to be sought in a form of some simple algorithm uniformly applied to each tessellatum of the system (e.g. as a low pass filter recommended in a number of papers on multiresolutional representation of images, or as an algorithm of quadrics-type universal tessella of the level).

Definite conditions should be satisfied for organization and processing of redundant information (knowledge) in the multi-resolutional systems. Providing a definite degree of redundancy is one of these conditions. A definite set of rules of incorporating the redundant information (knowledge) must be applied for the system proper functioning. The significance of proper dealing with redundancy of information (knowledge) is often overlooked. Several operators are discussed in [1] implicitly using redundancy of information (knowledge): generalization (abstraction), focusing of attention, etc. The following relationship is important for computer simulation of perceptual processes: among the total volume of information (knowledge) I_{TC} (for totality associated with the problem of control), and the size of minimal cell of distinguishability Δ required by the customer specifications.On the other hand, the number of resolution levels in the nested hierarchical system depends on the ratio I_{TC}/Δ. Phenomena of multi-resolutional redundant perceptual organization are linked with the phenomena of error propagation (see [31]).

5. Potential Capabilities and Perspectives of MRKP

Any intelligent module transforms (sometimes, irreversibly) the knowledge it deals with, and this transformation affects the subsequent computation processes, e.g. those of decision and control. Several types of knowledge transformation are reviewed. One of them called knowledge filtering (KF) can be characterized by its volume and rate. The detrimental effect of KF can be compensated by the corresponding level of knowledge redundancy (and by the subsequent redundancy of decision making processes, followed by the action redundancies as well).

MKR allows for coding the system as a whole and not as a result of selecting only its limited subset. This allows for a harmonious control of a system. In [34] an example is described of using MRKP system for intelligent control of the OSPREY process in the metallurgy. Another system is now in the process of development for a plasma deposition machine.

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[12] As in the Case 1 these generalizations are expected to simplify understanding, memorization, utilization, computation, and so on, of the tessellatum and its components. They can be in the form of rule tables, mathematical formulas, geometrical analogies, computational algorithms, and any another form applicable in the domain of interest.

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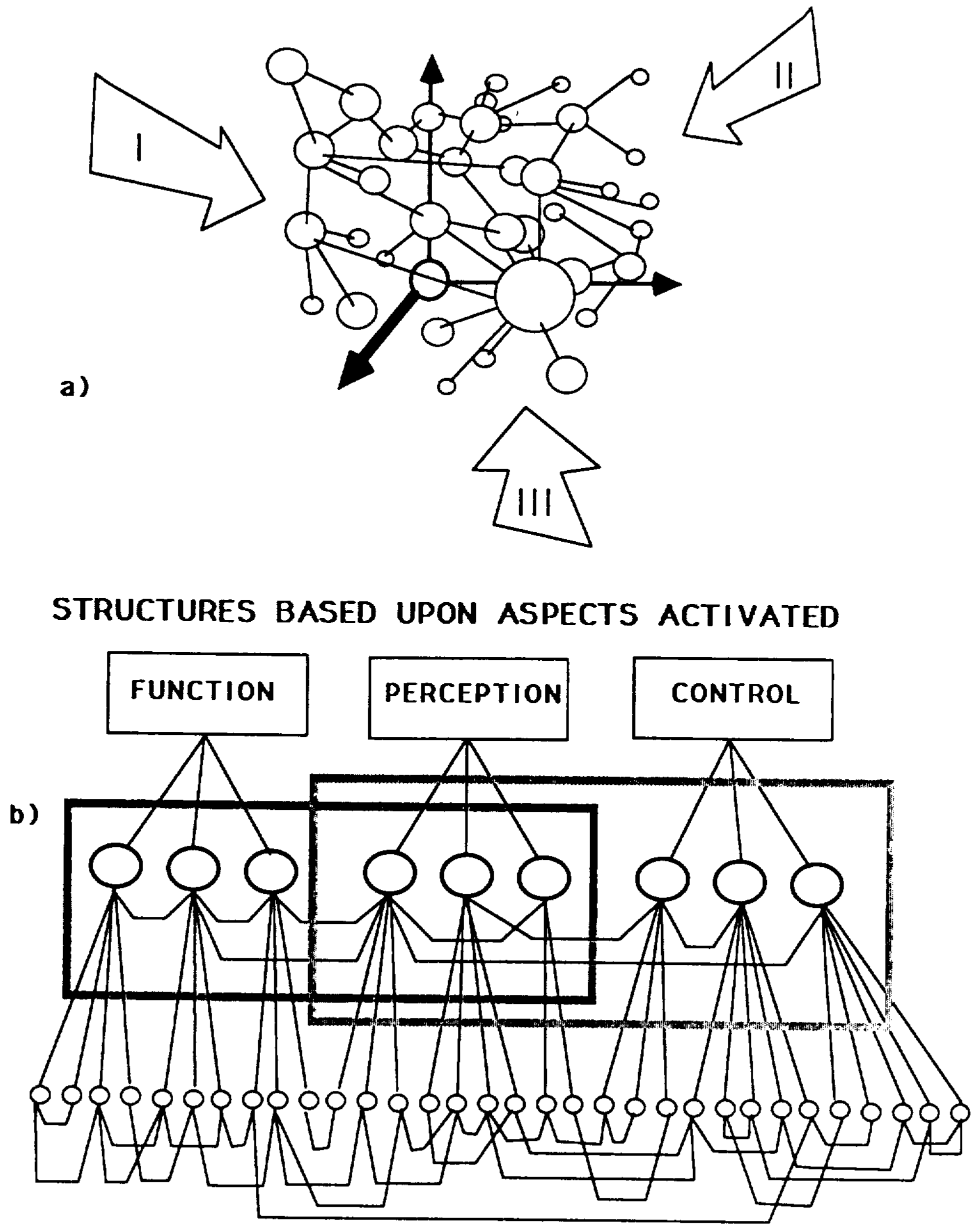

Figure 1. Full Heterostructure of the Chair

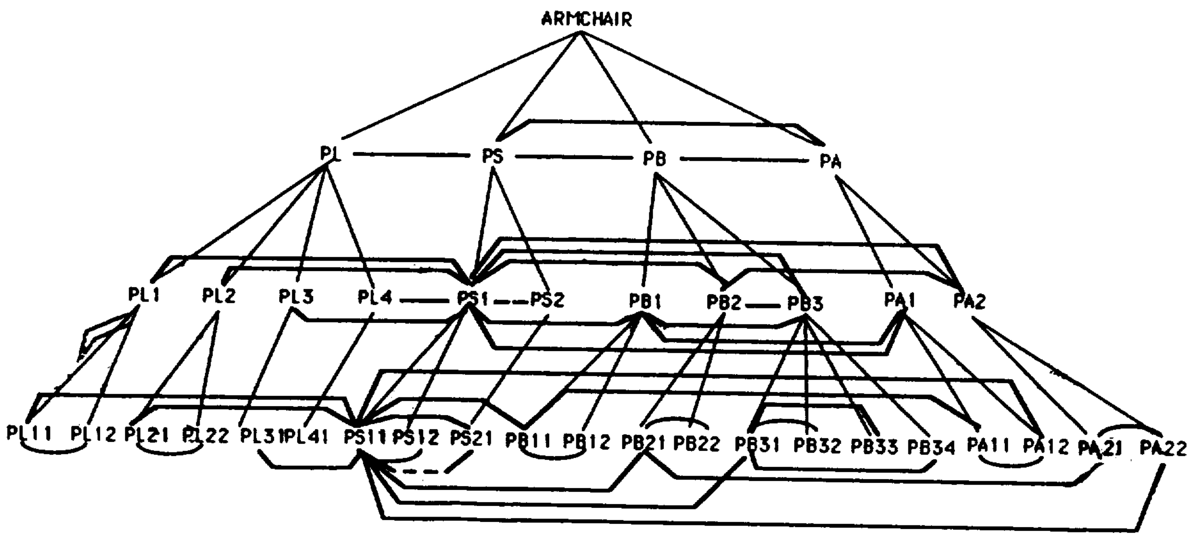

Figure 2. Graph of the Scope of perception

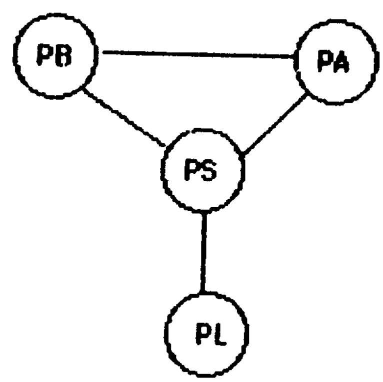

Figure 3. Tessellatum of the LR- level (low resolution) of the Perception Scope

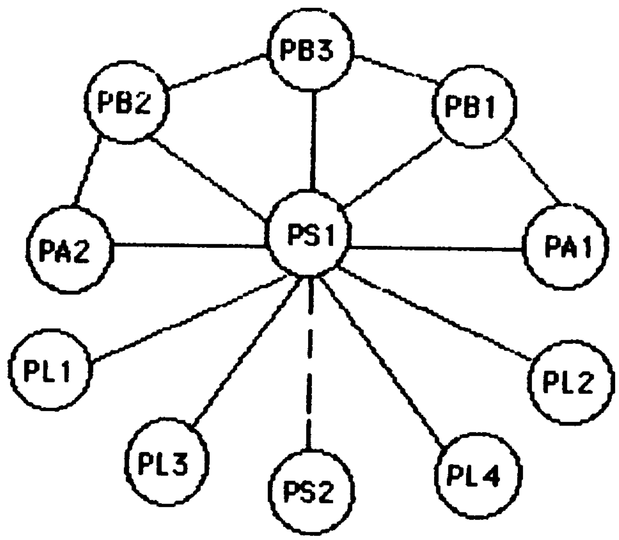

Figure 4. Tessellatum of the HR- level (high resolution) of the Perception Scope

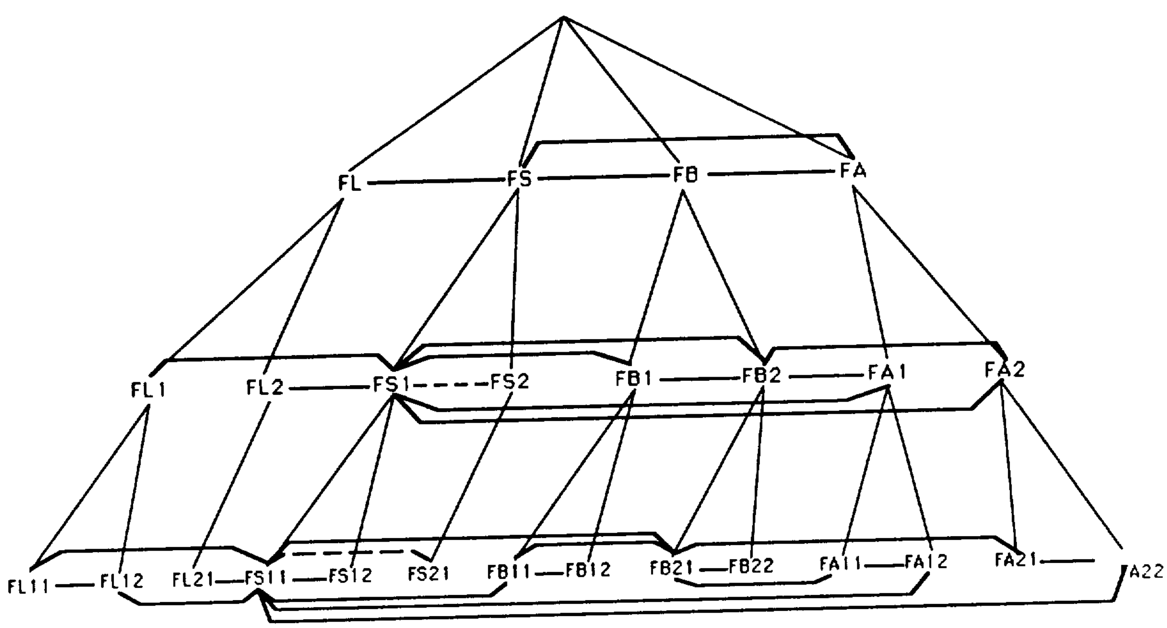

Figure 5. Graph of the Scope of Function

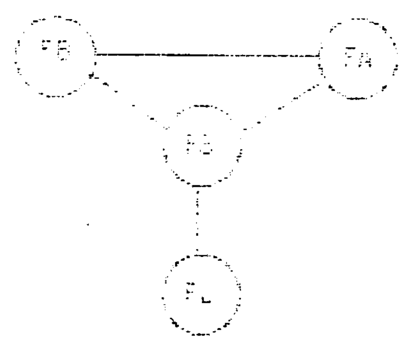

Figure 6.Tessellatum of the LR of the Scope of Function

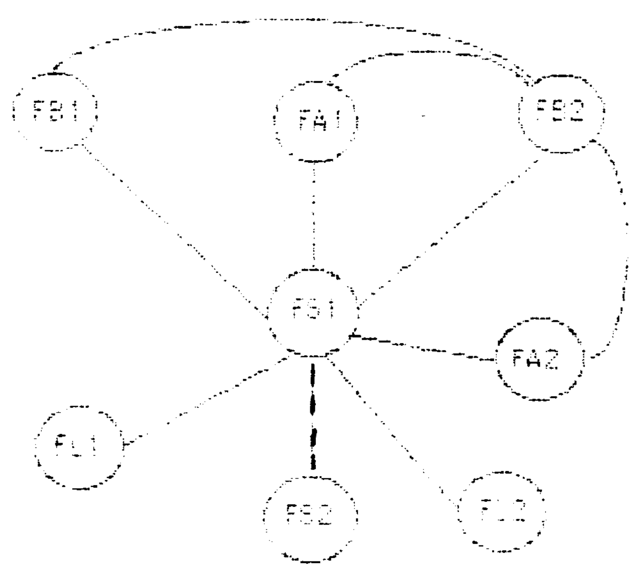

Figure 7. Tessellatum of the HR level of the Function Scope

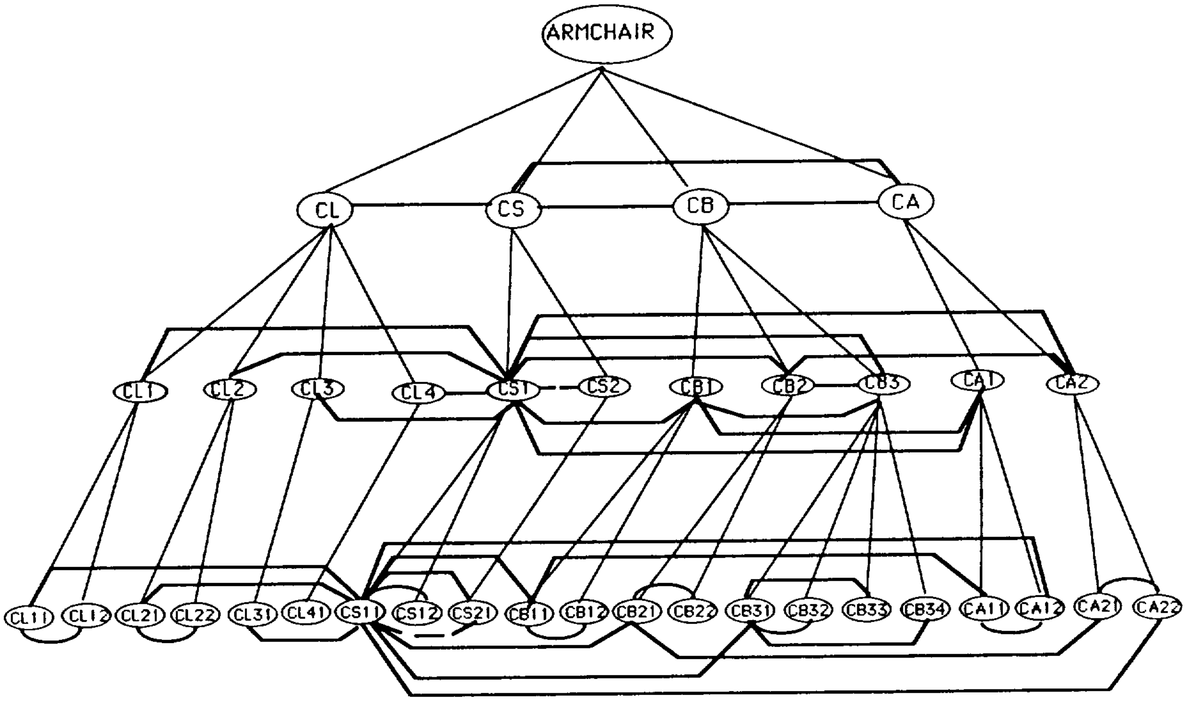

Figure 8. Graph of the Scope of Control (Assembly)

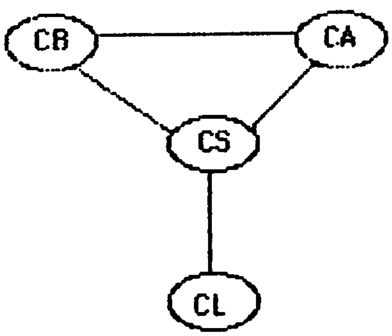

Figure 9.Tessellatum of the LR- level of the Control Scope

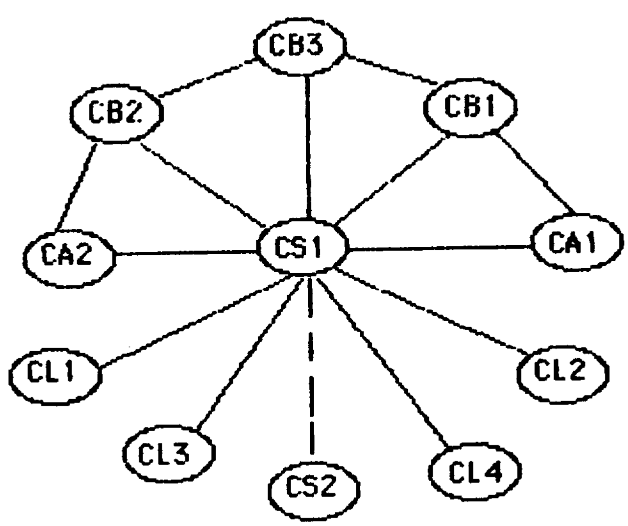

Figure 10.Tessellatum of the HR- level of the Control Scope