AN INTEGRATED SYSTEM FOR SYNTHESIS OF PLANT-WIDE CONTROL STRUCTURE

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ABSTRACT

A prototype integrated system and its theories for distributed SISO control structure synthesis of complete chemical plants is developed.

The scope of this work includes control structure synthesis not only of simple units with unspecified control loops but also of the complex process at preliminary and basic design stage.

Hierarchical approach and dual-decomposition strategy (that is multi-layer decomposition and multi-echelon decomposition) is applied to this system.

Because automatic control structure synthesis of complex plants is a problem defined as a series of knowledge-intensive tasks within multiple spaces, the established methodology is complemented by not only techniques from knowledge-based expert systems but also shortcut and rigorous control theories.

This system is used for education of control designers, process engineers, operators and students as well as for operability studying, in-line and on-line process control structure synthesis.

1. INTRODUCTION

Traditionally the stability analysis of control loops and parameter tuning have been treated in control system design using existing control theories after controlled variables, manipulated variables and the control structure were determined. However, as operating and capital costs rise, there is more incentive to design better control structure for chemical plants. 1970's there are many active researches on the concurrent design of whole process control structure in order to design effective control structure and to prevent redesign activities by integrating control structure design with other process design activities together with considering the complexity and interaction of the overall chemical process.

Recently much attention has been paid on developing expert systems in the field of process synthesis. Up to the present time, however, there is no publication on expert systems for process control structure synthesis expect a few paper.

Niida, Koshijima and Umeda[4] presented an experimental expert system for synthesizing distillation control structure which had been developed by using a commercially available inference engine, KEE (Knowledge Engineering Environment, from IntelliCorp).

Based on the experience gained by developing an experimental expert system for synthesizing distillation control structure, Niida and Umeda[5] developed an expert system applied to chemical process with various kinds of unit operations. This paper used two-level approach.

Shinskey[1] presented an expert system for an IBM personal computer. This expert system selects the most effective control structure for a distillation column based on relative gain analysis and estimates of integrated errors in response to load upsets.

Stephanopoulos et al.[2] proposed prototype intelligent system of human-aided control structure design, CONTROL-DESIGN-KIT. It was intended to provide all necessary facilities to support the needs of the new prototype intelligent system, needed for the design of control structure for chemical plants and the planning of plant-wide operational procedures. It has been developed on SYMBOLICS 3640 and 3650 computers, using ZETALISP and IntelliCorp's KEE system.

Birky et al.[3] developed an expert system for synthesis of distributed SISO control structure of distillation column, that is DICODE (DIstillation COntrol DEsign). Knowledge representation for the expert system is examined with particular emphasis on idiomatic control and its relationship to the GTST (Goal Tree Success Tree) knowledge structure. DICODE is implemented in the KES (Knowledge Engineering System, from Software Architecture and Engineering, Inc.) shell, primarily a backward chaining shell, with graphics provided by PLOT10 GKS (Graphical Kernel System, from Tektronix, Inc.).

2. MUTIPLE-SPACE APPROACH

For the synthesis of process control system, hierarchical approach and dual-decomposition strategy, that is multi-layer decomposition and multi-echelon decomposition, are used.

Thus, we decompose the problem space of process control system synthesis into as follows: First, decompose the control system into the optimum plant wide control and the unit-wise control. Second, decompose the process into independent subsystems (e.g. units). Third, decompose the control objectives into that of regulatory, optimizing, protective, secondary, etc. Fourth, decompose the model of process into that of steady-state, pseudo-steady-state and unsteady-state.

Therefore, above strategy is called as the "multiple-space approach". According to this approach, a certain component of the current control structure description cannot be implemented through existing technology and is further decomposed to implementable descriptions.

In hierachical approach, if we can identify and eliminate control problem by using steady-state models which are much simpler than the dynamic models, we can minimize our design effort because of considering only simpler steady-state models. And then, small perturbation and linear process dynamics regarded as pseudo-steady-state consideration are considered. Then, large perturbation and nonlinear dynamic response regarded as unsteady-state consideration are considered. Finally, the implementation of the control is considered (see Table 2.1).

Table 2.1 The hierarchical approach

level 1: steady-state consideration
(a) Controllability : Identify the economically significant disturbances, and ensure that there are an adequate number of manipulative variables in order to ba able to satisfy the process constraints and to optimize the operatng variables over the complete range of the anticipated disturbances.
(b) Operability : Ensure that there is close to the optimum amount of overdesign to be able to satisfy the process constraints and to minimize the "expected" operating costs for the complete range of anticipated disturbances.
(c) Select the controlled variables : Select a set of controlled variables so that the steady-state operating costs will be essentially minimized.
(d) Steady-state screening of control structures : Assess the amount of interaction in alternative control structures.

level 2 : normal dynamic operation - small perturbation from steady state
(a) Inventory control : Ensure that the plant material and energy balances can be closed, and asses the need for intermediate storage capacity.
(b) Dynamic control : Asses the stability of the control structure alternatives, and ensure robustness. The analysis includes flow-shheet modifications(e.g., additional overdesign) to ensure process operability in the dynamic state.

level 3 : abnormal dynamic operation
(a) Start-up and shut-down : Asses the need for special control systems for the start-up and shut-down of the plant.
(b) Diagnostics and failure recovery : Ensure safe operation when equipment failures are encountered

level 4 : Imprementation
(a) Ditributed control : Organize the levels of local unit control, plant control, and supervisory control.
(b) Human interface : Ensure that the operators can operate the plant.

In case of multi-layer decomposition (that is the decomposition of control objectives into that of regulatory, optimizing, protective, secondary, etc.), the synthetic strategy is as follows: First of all, determine the regulatory and optimizing control system using the branch-and-bound technology. Then, determine the other control objectives using the decision tree and idiomatic control design methodology (see Figure 2.1).

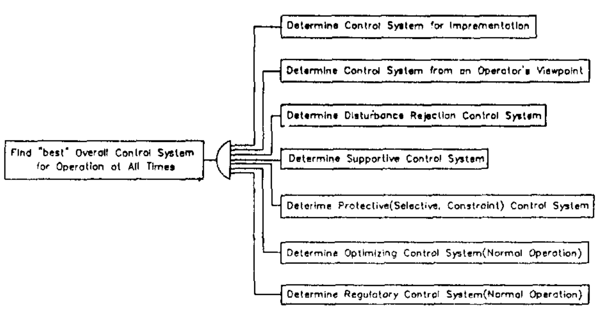

Figure 2.1 The multi-layer decomposition

In case of multi-echelon decomposition (that is the decomposition of process into subsystems), the synthetic strategy is as follows: First, determine the control configurations which will handle optimum plant-wide operations. Second, divide the process into separate independent blocks. Third, determine the degree of freedom and the number of controlled and manipulated variables for each block. Fourth, synthesize the control loops of the various blocks. Fifth, coordinate the conflicts among the control loops of the various blocks. Sixth, improve the coordinated control configurations among various blocks and the optimum plant-wide control configurations using some heuristics related to recycle stream and ratio control schemes (see Figure 2.2).

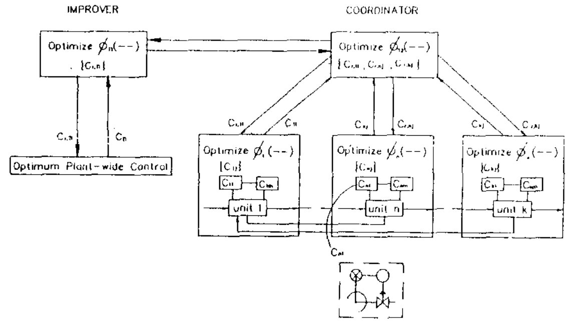

Figure 2.2 The multi-echelon decomposition

The screening procedure for branch-and-bound technology is as follows: First, use the robust engineering heuristics to reject unacceptable solutions. Second, use the interaction analysis, the disturbance rejection analysis and the stability analysis under steady-state. Third, use the simple dynamic measures such as time constants, timelags, etc. Fourth, use the interaction analysis under unsteady-state (see Figure 2.3).

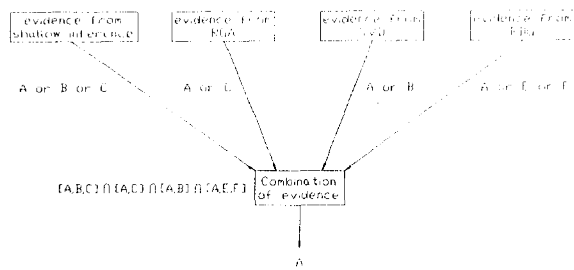

Figure 2.3 The parallel screening approach

The structure of an integrated system and general designing procedure for process control structure synthesis are presented in Figure 2.4 and 2.5.

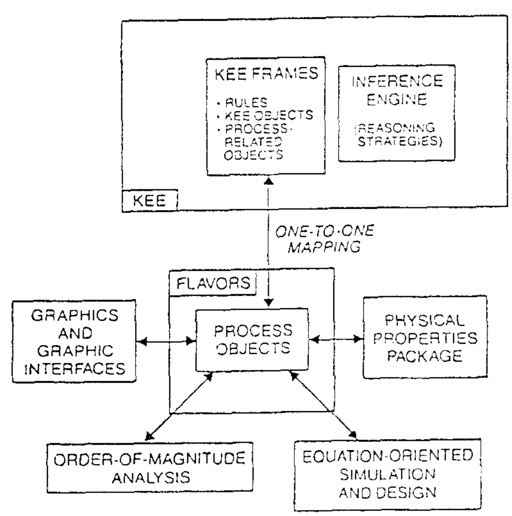

Figure 2.4 The structure of an integrated system

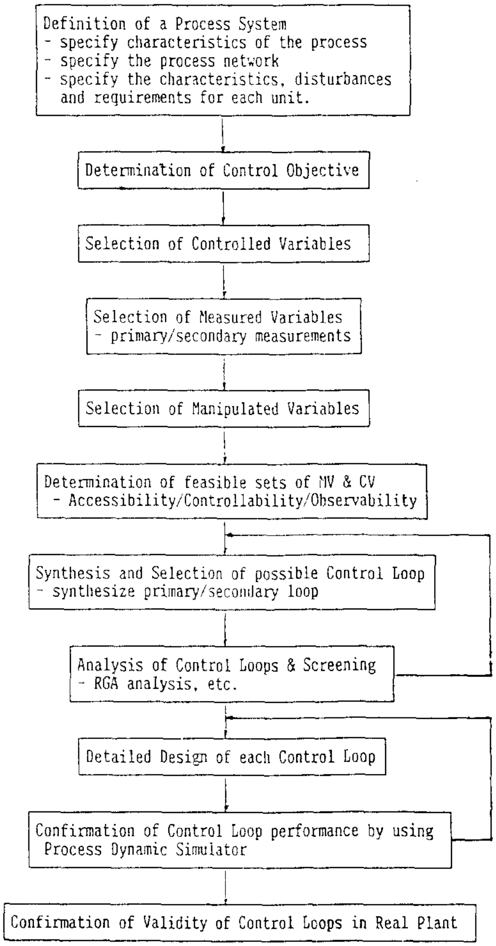

Figure 2.5 The general designing procedure

3. OPTIMUM PLANT-WIDE CONTROL

Although a plant is usually designed for a nominal production rate, a design tolerance is always incorporated because the market conditions may require an increase or decrease from the current rate. The control system is then called to ensure a smooth and safe transition from the old to the new production level. This is called as "optimum plant-wide control," because its purpose is to direct the control action in such a way as to make the conflicts equal to the outflows and achieve a new steady-state material balance for the plant.

Changes in the production rate come from the plant's management and are rather infrequent (e.g., once every two weeks, or a month, or longer period). The time required by the plant to reach the new operating level is much shorter than the periods noted above. Consequently the transient dynamic behavior is very short-lived and not very important. Therefore, we can assume that the plant always operates at steady-state. It is clear, then, that steady-state balances are sufficient for plant-wide control.

We use the results of optimum steady-state control analysis to generate heuristics for plant-wide control in much the same way that heuristics have been developed for setting the values of certain design variables to aid in flowsheet design and synthesis. Some heuristics[7] for plant-wide control are presented in Table 3-1.

Table 3.1 Some heuristics for optimum plant-wide control

- Production rate : compensate changes in the production rate by manipulating the fresh feed rate of the limiting reactant
- Processes with a gas recycle and purge : keep the gas recycle flow constant at its maximum value.
- Reactor heating/cooling : depending on the process
  (a) If the product distribution is improved by operating at low temperatures, operate the reactor cooling system to achieve the lowest possible temperature.
  (b) For complex reactions where the product distribution is insensitive to temperature, adjust the reactor temperature to maintain the recycle flow of the limiting reactant constant at its maximum possible value.
  (c) For sngle reactions and liquid feed, adjust the reactor temperature to achieve the maximum recycle flow of the limiting reactant(if stream for the recycle column is cheaper than incremental fuel) or maximize the temperature to obtain the largest possible conversion(if incremental fuel is cheaper than incremental steam).
- Feed rate of the nonlimiting reactant : depending on the process
  (a) Adjust the feed rate to satisfy a molar ratio constraint at the reactor inlet.
  (b) If the product distribution improves as the molar ratio at the reactor inlet increases, adjust the feed rate to keep the recycle flow of the nonlimiting reactant at its largest possible value.
  (c) If the product distribution is independant of the molar ratio and the nonlimiting reactant is a liquid, use a ratio controller to the limiting reactant.
- Flash drum temperature : maximize the cooling water return temperature

4. UNIT-WISE CONTROL

According to the multiple-space approach, decision trees are made. These decision trees are the same architecture as the knowledge base of an expert system. As an example, consider a distillation column.

The root goal of decision tree for distillation column is to find the best overall control structure for column operation at all times. This goal is broken into the first level of subgoals (see Figure 5.1).

The goal of determining the best regulatory control structure for normal operation normally involves optimizing the column operation. We decomposed the regulatory control objectives into product quality control and material balance control. Next, the product quality control can be decomposed into dual-composition (temperature) control, single-composition (temperature) control and flow control. And then, the material balance control can be decomposed into reflux drum level control, column base level control and distillation pressure control (see Figure 5.2).

The goal of the protective (selective or constraint) control objectives is to guarantee safe operation at constraints. Determination of the protective controls includes use of override control loops.

The best regulatory and protective control (primary controls) can be improved by using some supportive control (secondary control) structure. Determination of the supportive controls for improved performance includes use of cascade and feedforward control loops.

Moreover, additional control loops are often added to conventional configurations to isolate the column from measurable and controllable disturbances. These loops require only standard instrumentation and simple computing elements. The loops to be considered are feed enthalpy control, internal reflux, etc.

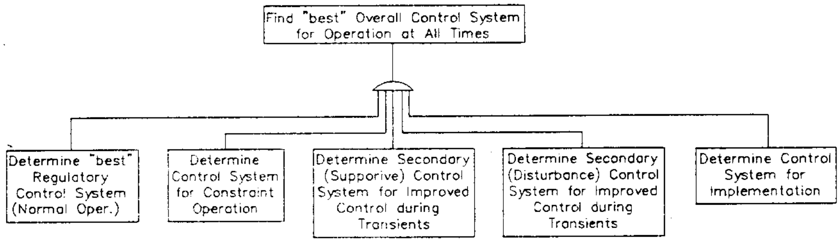

Figure 5.1 The decision tree for overall control structure

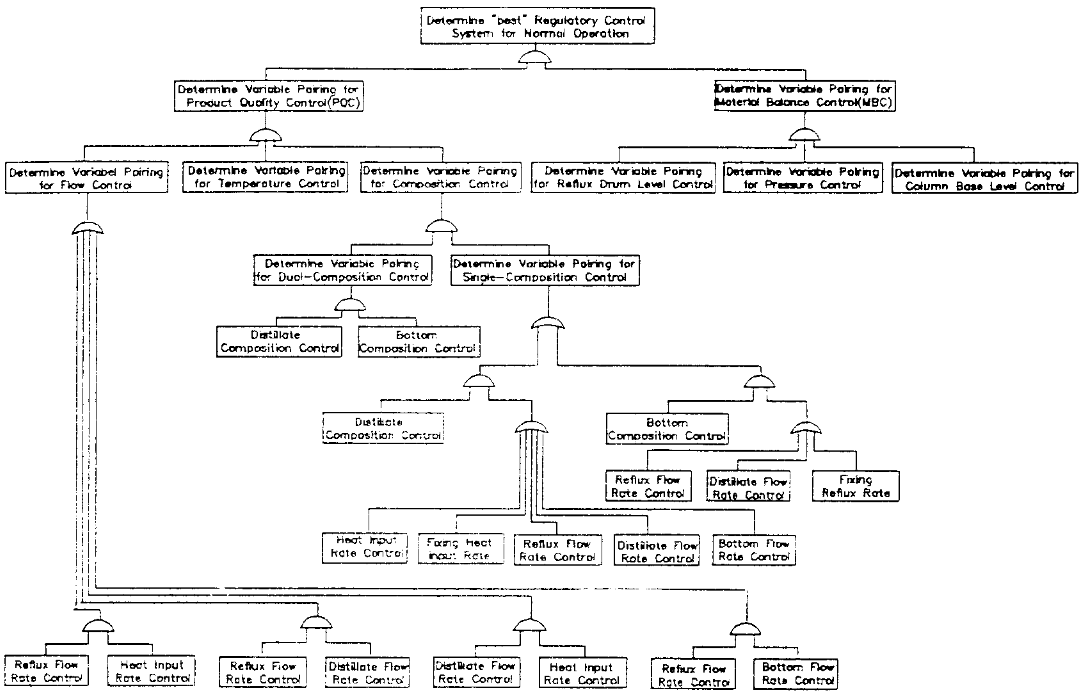

Figure 5.2 The decision tree for regulatory control structure

In order to implement the control structure which has been outlined above, the objectives must be translated into the idioms and placed in the proper arrangement.

5. REGULATORY CONTROL SYSTEM SYNTHESIS

The regulatory control structure synthesis is typical combinatorial problem. Furthermore, because the regulatory controlled variables are changed according to the given situation, we must cope with this condition.

Therefore, the general strategy this implementation uses to solve regulatory control structure synthesis is to generate all possible combinations of controlled variable and manipulated variable and to then eliminate impossible combinations until only solutions that meet all problem constraints remain.

The combinations are generated via forward chaining using new world action rules. The expression of problem constraints uses values class, cardinality and deduction rules.

The generation of worlds (alternatives) representing partial and total combinations of controlled variable and manipulated variable is handled by two new world action rules, the GUESSING.RULE and the ANSWER.RULE.

The GUESSING.RULE causes a new world to be called for each possible combination of manipulated variable for each controlled variable. Some of these worlds are immediately made inconsistent either by value class violations or by the application rules.

```
* GUESSING.RULE

  (IF (?CV IS IN CVS)
      (?MV IS IN MVS)
      THEN
      IN.NEW.AND.WORLD
      (THE MV OF ?CV IS ?MV))
```

The ANSWER.RULE combines sets of worlds created by the GUESSING.RULE. The majority of the worlds created by the ANSWER.RULE are made inconsistent because the NO.MV.DUPLICATION.RULE apply to eliminate worlds with more than one controlled variable with the same manipulated variable.

```
• ANSWER.RULE

 (IF (THE MV OF C-A IS ?A)
    (THE MV OF C-B IS ?B)
          .
          .
    THEN
    IN.NEW.WORLD
    (TEXT (THERE IS A SOLUTION!)
    (LISP
     (FORMAT T "~%~%SOLUTION IN WORLD~D"
          (GET.WORLD.NAME ?$WORLD$)))
    (LISP
     (FORMAT T
          "~% C-A : ~D~D"
          ?A
          (GET.VALUE 'C-A 'MV 'OWN
                    ?$WORLD$)))
    (LISP
     (FORMAT T
          "~% C-B : ~D~D"
          ?B
          (GET.VALUE 'C-B 'MV 'OWN
                    ?$WORLD$)))
          .
          .               )
```

To implement above strategy, TMS (Truth Maintenance System), KEEworlds and deduction rules of IntelliCorp's KEE (expert shell) are used.

```
* C-BOTTOM.RATIO.1.RULE

  (WHILE (THE MV OF C-C-MB IS C-M-B)
       (THE B-RATIO OF C-NUMBER
        IS EXTREMELY-SMALL)
       BELIEVE FALSE)
          .
* C-REFLUX.RATIO.1.RULE

  (WHILE (THE MV OF C-C-MD IS C-M-L)
       (THE R-RATIO OF C-NUMBER IS ?RR)
       (LISP (<= ?RR 1)
       BELIEVE FALSE)
```

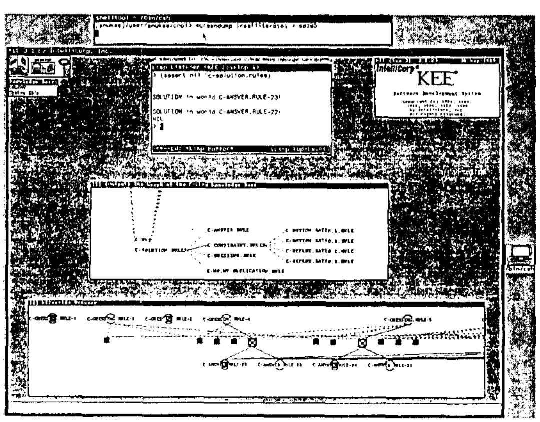

Figure 4.1 KEEworlds and TMS

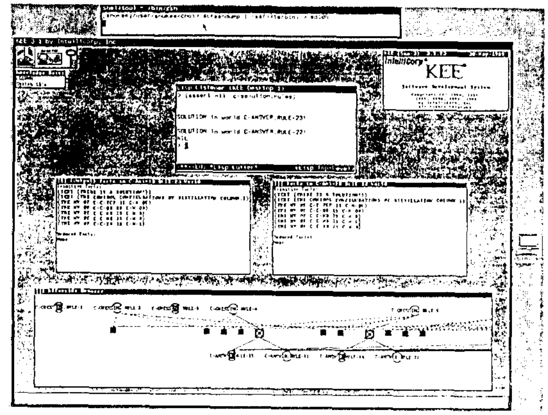

Figure 4.2 The explanation about true worlds

To choose various controlled variables according to given situation, MENU and WIDOW facilities are reinforced.

The implementation of this problem extensively takes advantage of the TMS to enforce the problem constraints. This makes it quite easy to write simple, general rules to generate and merge new worlds, without worrying about contradicting the conditions of the problem. This branch-and bound technology is a relatively general, efficient method in the field of artificial intelligence.

6. COORDINATOR and IMPROVER

COORDINATOR is to eliminate conflicts among the control systems of the various blocks. The control configuration resulting in recombing the blocks usually lead to an overspecification of the overall controlled process. This can be explained as follows. Consider two units connected by a common flow. When we design the loops for each unit separately,it is possible to select the interconnecting flow as a controlled variable for both units but in different loops. Also, it is possible to have the common interconnecting flow as the manipulated variable in two different control loops. Both situations are called "type-1" conflicts (see Figure 6.1).

Futhermore, under normal steady-state operation, other conflicts as well as above conflicts can be found and thus eliminated. We call these situations "type-2" conflicts (see Figure 6.2).

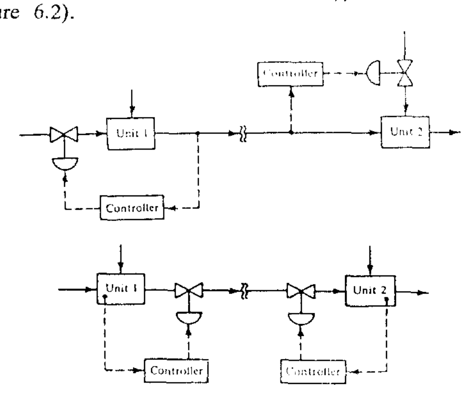

Figure 6.1 The type-1 conflicts

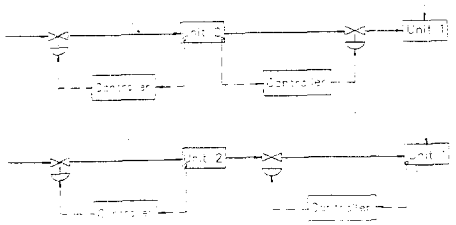

Figure 6.2 The type-2 conflicts

The solution strategy for COORDINATOR is as follows: First, specify the relationship and characteristics of process and control system. Second, find overspecifications like type-1 conflicts. Third, determine the priority for control loops conflicted. Fourth, eliminate low priority control loop. Fifth, find the recycle loops using the loopfinder algorithm. Sixth, find type-2 conficts in each recycle loop. Repeat the third and fourth steps.

In addition to plant-wide control and coordinated unit-wise control, some improved/advanced control schemes such as the control schemes related to recycle streams and ratio control schemes need to be considered. These considerations are included within IMPROVER.

7. IDIOMATIC CONTROL SYNTHESIS

The concept of control idioms was introduced as a way of defining mini-inventions which control design engineers use when designing a control structure for a process. Control idioms can be identified by applying the idiomatic control analysis methodology to various processes, and compiling a table of the resulting idioms with their purposes. Many control idioms are system independent, however, some are unique to specific processes.

To use idiomatic control to build a control structure, the control objectives must be defined completely. First, the primary control objectives (i.e. regulatory and protective) are specified. Next, the basic regulatory control structure is synthesized. And then, the secondary objectives of stabilization and anticipation (i.e. cascades and feedforwards) are specified. After the control objectives have been specified, those except the regulatory control objectives are translated into idioms with a one-to-one pairing of objectives and idioms.

8. CONCLUSION

The scope of this work includes the control structure synthesis of not only simple units with unspecified control loop structure but also complex process at preliminary and basic design stage. Moreover, control structure synthesis of complex process at advanced/final design stage and control law synthesis about specified control structure of simple units will be developed later (see Figure 8.1).

The development of such a system requires new computing environments based on LISP machines, and new programing styles whose central features are; object-oriented programming and data- or result-driven procedural programming. Thus AI technology is used for building above system. Frame, production rule, semantic netwok and object-oriented programming is used for knowledge representation and control strategy for inference is forward-chaining and search strategy is the depth-first search. TMS (Truth Maintenance System), KEEworlds and KEEinterfaces (Menu, Keepicture, Activeimage, etc.) support the expert system.

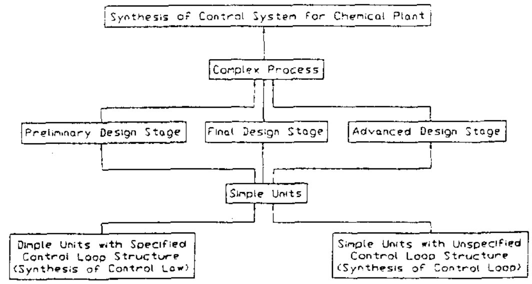

Figure 8.1 The classification of control structure synthesis problems

Furthermore, modular developments of sensitivity analysis for selection of control objectives, of structural analysis for finding sets of controlled and manipulated variables, of interaction analysis (RGA, SVD), disturbance rejection analysis (RDG) and stability analysis (Niederlinski's theorem) for screening the control structure alternatives is also included.

Many problems still have to be resolved, before a complete prototype is operational, the most important of which are as follows: First, have to do the more effecient control of the designing process. Second, have to make the extensive use of the presently developed system for the synthesis of process control systems of other unit operations. Third, while the current scope of the prototype deals only with the SISO design problem, system structure and extensibility issues will carry over to the MIMO version. Fourth, user interfaces such as menu, graphic, window and explaining facility will have to be reinforced. Fifth, dynamic interaction measurement index will also be added. Sixth, in case of designing the inferential control, it is required to determine the sensor loaction and type. Seventh, the automation of "machine learning" during design will be done.

9. REFERENCE

[1] F.G. Shinskey, "An Expert System For the Design of Distillation Controls," Proc. of C.P.C. III, Asilomar, California, January 12-17, pp. 895-912, 1986.

[2] G. Stephanopoulos, J. Johnston and R. Lakshmanan, " An Artificial Intelligence Perspective in the Design of Control Systems for Complete Chemical Processes," The Shell Process Control Workshop, pp. 49-78, 1987.

[3] G.J. Birky, T.J. McAvoy and M. Modarres, "An Expert System for Distillation Control Design," Comp. and Chem. Eng., Vol. 12, No. 9/10, pp. 1045-1063, 1988.

[4] K. Niida, I. Koshijima and T. Umeda, "Distillation Control System Synthesis by Expert System," World Cong. III of Chem. Eng., Tokyo, pp. 562-565, 1986.

[5] K.Niida and T.Umeda, "Process Control System Synthesis by an Expert System," Proc. of C.P.C. III, Asilomar, California, January 12-17, pp. 869-894, 1986.

[6] W.R. Fisher, M.F. Doherty and J.M. Douglas, "The Interface between Design and Control. 1. Process Controllability," Ind. Eng. Chem. Res., 27, pp. 597-605, 1988.

[7] W.R. Fisher, M.F. Doherty and J.M. douglas, "The Interface between Design and Control. 3. Selecting a set of Controlled Variables," Ind. Eng. Chem. Res., 27, pp. 611-615, 1988.