

AN EXPERT SYSTEM FOR RESTRUCTURABLE CONTROL

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ABSTRACT

Work in progress on an expert system which restructures and tunes control systems on-line in real-time is presented. The expert system coordinates the different methods involved in redesigning and implementing the control strategies due to plant changes.

INTRODUCTION

A restructurable control system has the ability to redesign itself on-line to compensate for a significant change in the plant. Restructurability is a valuable feature because it allows a closed-loop system to continue operating in an acceptable manner even in the face of major changes to the plant. Examples of plants with major changes are aircraft with battle damage or engines with foreign object damage. With an invariant control system designed for the original plant, an aircraft that experienced battle damage may now only be able to limp home. In the worst case it would be unstable and crash. With a redesigned control system for the new, altered plant, the plane may be able to carry out all or part of its mission with only slightly reduced capabilities and it is more likely that it will return safely.

Restructurable control is applicable to mechanical problems such as actuator or control surface failures. Most of the redesign strategies in the literature work by redistributing the forces and moments of the failed actuator or missing surface over the remaining components to compensate for the lost components. The research by Looze, et al has concentrated on a linear quadratic approach to the redesign procedure [1]. Horowitz, et al have applied quantitative feedback theory to

control system reconfiguration [2]. Raza and Silverthorn have used the pseudoinverse of the control matrix and generalized input vectors to achieve the desired responses along orthogonal axes [3]. The technique in [3] is similar to the control mixer concept for reconfiguration described by Rattan [4].

The goal of this paper is to describe a way to tie together some of the previous work in the field so as to achieve a highly survivable control system. A highly survivable system can successfully restructure in response to a multitude of different failures. In general, previous restructurable controllers have been specifically designed for a single failure type. Each design method used is valid for its specific application. However, none is "optimal" nor even applicable in all situations. Thus, to achieve a highly survivable system, it is necessary to identify the current dynamic characteristics of the plant and to determine which of the possible solutions is the best in some sense under the given circumstances. To accomplish this decision making in an uncertain environment with potentially conflicting mission objectives, some type of intelligence will be required. Hence the concept of an expert system to coordinate the different redesign strategies is proposed.

An expert system consists of three independent parts: an inference engine, a rule base, and a knowledge base. The rule base is a set of heuristics or rules-of-thumb which apply to the type of problem at hand. The knowledge base is a collection of information specific to the current situation. The inference engine is a program which applies the rules to the knowledge base in order to glean new information or to determine if an assumption is justified. When new

information is asserted, it is stored in the knowledge base.

BACKGROUND

The idea of restructurable control has appeared recently, mainly with respect to aircraft. Battle damage has been considered a perfect application for the research. Commercial airliners are also a possible vehicle for the work. Several accidents and near accidents where the pilot was able to recover and land the plane after analyzing the problem have been discussed in relation to restructurable control [5].

Thus this strategy is very attractive for both civilian and military aeronautics and propulsion applications. Creating the ability in a plane to restructure its control system after damage to continue at a level of performance similar to its original design specifications is highly desirable. It is also important to remember that the main ideas here are not limited to airplanes. They can be applied to a wide variety of systems with inherent redundancy.

EXPERT SYSTEM COMPONENTS

The proposed overall structure of the expert system is shown in Figure 1. It consists of (1) an inference engine, (2) a control system restructuring knowledge and rule base, and (3) a controller tuning knowledge and rule base. The control system restructurer is already partially implemented. In the future we plan to incorporate an on-line controller tuning expert system into the overall system. It will share the inference engine with the reconfiguration expert system.

An inference engine can work with any appropriately structured knowledge base and rule base; it is not linked in any way to the application. Likewise, a rule base can be used with any appropriate knowledge base.

The inference engine developed for this application is capable of performing symbolic and numerical calculations required to evaluate certain rules. It can also execute generalized rules with previously established facts from the knowledge base to infer new facts. In addition, it has the ability to perform what-if type reasoning by trying different scenarios if more than one is appropriate.

The knowledge base of the restructurable

control system consists of information about the plant and control systems. For a linear system such parameters as the system matrices and the original controller gains are stored. There are also specifications on the actuators such as linear ranges and characteristics. Information stored here can change in response to plant changes. It is changed or updated as new facts become available.

The rule base of the control system restructurer contains rules about control system design. These range from top-level control design methods to low-level details such as definitions of controllability and observability. The rules may contain numerical expressions to be evaluated (such as whether a realization is minimal) and may contain variables to be given values by the inference engine during the discovery of new facts.

A separate knowledge base will be required for the tuning system. It will contain response characteristics associated with a well-tuned loop of the type in question. It also will have data on the previous responses obtained in the tuning process.

A rule base for controller tuning will be created also. The heuristics will use the previous tuning and plant information to determine an appropriate tuning paradigm.

Figure 2 shows the interaction of the two expert systems with the overall system.

SYSTEM CAPABILITIES

Figure 3 shows the anticipated future setup of the overall system. It shows a hierarchy with an expert system receiving information from a system identifier and a pattern extractor. This information is used in the restructuring of the controller for the altered plant. In the current setup, the plant simulation, the controller, and the expert system are all written in compiled LISP running on an LMI Lambda LISP machine. The system identifier and the pattern extractor are not yet implemented. The simulation consists of a realization of a linearized system in the form of matrices (A,B,C,D) and the states are evolved using Euler integration. Presently the expert system uses a model of the plant directly from the simulation. The linear model is of the form

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

A change in the model prompts the expert system to analyze and redesign the control. The new controller replaces the old one in the simulation and the states continue to evolve.

The restructuring strategies that the expert system can currently use involve the pseudoinverse of B [3,4]. The expert system takes a realization (A,B,C) and manipulates it, using the Kalman Structure Theorem for instance, until it is minimal and $B'B$ has full rank. If the expert system can achieve this goal, the equation

$$K = (B^T B)^{-1} B^T (A - (A_0 - B_0 K_0))$$

is used to determine the new controller matrix. Here A and B are the altered system matrices and $(A_0 - B_0 K_0)$ is the reduced order version of the closed-loop system matrix of the full order model.

Examples of the heuristics used in the situation described above are:

1. if (A,B,C) is controllable and observable
then realization is minimal
2. if $B^T B$ is full rank
then pseudoinverse of B exists
3. if (A,B,C) is not minimal and (A,B,C) is minimum phase
then find a minimal realization
4. if pseudoinverse of B exists and realization is minimal
then
$$K = (B^T B)^{-1} B^T (A - (A_0 - B_0 K_0))$$

These rules, presented here in pseudo-code, are the type of heuristics contained in the rule base.

A user interface exists for use in the development stage. In a delivery system there will be no need for such an environment as the system will run without human intervention.

The expert system runs only when invoked, for example when the control needs to be redesigned. Currently, it is invoked by manually stopping the simulation and running the expert system. The simulation must then be restarted. This is necessary at present because the simulation and the expert system both run on the same processor and no system identification scheme has yet been implemented. In the future the identifier will communicate with the expert system and cause it to start redesigning when a significant change in the system matrices occur.

CONCLUDING REMARKS

The expert system is able to handle a variety of reconfiguration situations. For these cases, the new controller is designed and implemented in a matter of seconds. Naturally the redesign time depends on the order of the system.

At present a few of the control design algorithms from the literature have been implemented. More have to be included in addition to incorporating any other work, both new and existing, that is deemed necessary for the system to work well.

Some work has been done in the area of controller tuning by pattern recognition techniques for single-input single-output systems [6]. We intend to extend the methodology to multiple-input-multiple-output systems.

Currently the LISP machine is doing the numerical calculations. For the system to run in real time, the number crunching will have to be moved off the LISP processor to a numeric processor such as an array processor.

A system identifier will be implemented in the future. In the near term one might be implemented on the LISP machine. Eventually a microprocessor-based system identifier should be connected to the plant and signal the expert system if a significant change occurs in the model.

An on-line pattern extractor which will determine the response features will also have to be developed. These features will be passed to the knowledge base of the tuning expert system.

The simulation currently residing within the Lambda will be moved to an Applied Dynamics AD100 simulation computer. This will allow a full nonlinear simulation to be implemented and it will run in real time. When the interface between the two is completed, the capability will exist to test the expert system in a realistic situation.

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