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An Expert System to Perform On-Line Controller Restructuring for Abrupt Model Changes

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AN EXPERT SYSTEM TO PERFORM ON-LINE CONTROLLER RESTRUCTURING FOR ABRUPT MODEL CHANGES*

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ABSTRACT

Work in progress on an expert system used to reconfigure and tune airframe/engine control systems on-line in real time in response to battle damage or structural failures is presented. The closed loop system is monitored constantly for changes in structure and performance, the detection of which prompts the expert system to choose and apply a particular control restructuring algorithm based on the type and severity of the damage. Each algorithm is designed to handle specific types of failures and each is applicable only in certain situations. The expert system uses information about the system model to identify the failure and to select the technique best suited to compensate for it. A depth-first search is used to find a solution. Once the new controller is designed and implemented it must be tuned to recover the original closed-loop handling qualities and responsiveness from the degraded system. Ideally, the pilot should not be able to tell the difference between the original and redesigned systems. The key is that the system must have inherent redundancy so that degraded or missing capabilities can be restored by creative use of alternate functionalities. With enough redundancy in the control system, minor battle damage affecting individual control surfaces or actuators, compressor efficiency, etc. can be compensated for such that the closed-loop performance is not noticeably altered. The work is applied to a Black Hawk/T700 system.

INTRODUCTION

A restructurable control system has the ability to redesign itself on-line in real time to compensate for a detectable change in the system. Here the closed-loop system consists of a controller and the dynamical system being controlled, henceforth known as the plant (figure 1). A detectable change is defined as an excursion of the identified system model from the range which is considered normal, indicating possible damage to the closed-loop system. The ability to restructure is important to mission effectiveness because it allows a closed-loop system to continue operating in an acceptable manner even after changes to the system. Examples of systems which

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undergo sudden changes are aircraft with battle damage or engines with foreign object damage. With an invariant control system designed for the nominal plant, an aircraft which has experienced battle damage may be just barely operable. In the worst case it would be unstable. With a redesigned control system for the new, altered plant, the aircraft is more likely to return safely and it may be able to carry out all or part of its mission with only slightly reduced capabilities.

Restructurable control is applicable to systems which experience mechanical problems such as actuator or control surface failures and where the capability lost due to failure is at least partially available in some other component or components. For example, compressor degradation caused by foreign object damage results in the need to run at a higher temperature to obtain a desired thrust. This might be achieved by adjusting the fuel valve, an engine actuator, to increase the fuel/air ratio. Most of the redesign strategies in the literature attempt to redistribute the forces and moments of the failed actuators or missing surfaces over the remaining redundant components to compensate for the lost capabilities. The methods differ in the redesign approach they employ. The research by Looze, et al has concentrated on a linear quadratic approach to the redesign procedure [1]. Horowitz has applied quantitative feedback theory to the initial design of a fixed compensator capable of handling failures and thus avoids the control system reconfiguration problem totally [2]. Ostroff and Hueschen have used the Proportional-Integral-Filter with Command Generator Tracking, a direct digital integrated formulation [3]. Raza and Silverthorn have used the pseudoinverse of the control matrix and generalized input vectors to achieve the desired responses along orthogonal (longitudinal, latitudinal, and directional) axes [4]. This last technique is similar to the control mixer concept for reconfiguration described by Rattan [5].

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 system 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.

BACKGROUND

The idea of restructurable control has appeared recently, mainly with respect to aircraft. Battle damage has been considered an ideal application for the research. Several accidents and near accidents involving airliners where the pilot was able to recover and land the aircraft after analyzing the problem have been used as justification for introducing restructurable control to the commercial sector as well [6]. A good example of a pilot manually integrating an engine and airframe control to reconfigure the system appears in [7] where power was used to achieve both pitch and directional authority after complete hydraulic failure. If the expert system could augment the pilot's ability by adapting the control system to compensate for the damage, the pilot's burden would be lessened and he would be free to carry out the mission objectives.

Creating the ability for an aircraft to restructure its control system after damage to continue at a level of performance similar to its original design specifications is highly desirable. Thus this strategy is very attractive for both civilian and military aeronautics and propulsion applications. In addition, the main ideas presented here are not limited to aircraft—they can be applied to a wide variety of systems with inherent redundancy.

EXPERT SYSTEM COMPONENTS

Generally, an expert system consists of three independent parts: a rule base, a knowledge base, and an inference engine—a mechanism for deducing new information. The rule base is usually a set of heuristics or rules-of-thumb which apply to the general type of problem at hand, for example control system design. The knowledge base is a collection of data specific to the current situation such as the particular plant under control. The inference engine is an algorithm 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 inferred or otherwise obtained, it is stored in the knowledge base.

The basic model for the inference engine used in this work comes from [8] but many features have been added to make it more powerful. Some of these include: the ability to perform numerical calculations required to evaluate certain rules; the ability to remove or replace assertions in the knowledge base; the ability to parse certain English-like phrases during the evaluation of rules; the ability to perform "what-if" type reasoning by trying different scenarios if more than one is appropriate. The original inference engine in [8] is capable of performing symbolic pattern matching with wildcards to evaluate rules. Using previously established assertions from the knowledge base it is able to infer new information. All of the functionality of the original inference engine is retained.

An inference engine can work with any appropriately structured knowledge base and rule base. This three part structure allows the inference engine to be application-independent while the application-dependent information resides in the rule base and the facts about the specific instance are stored in the knowledge base. In other words, the rule base might apply to control system design for rotary wing aircraft/engine systems in general while the knowledge base might contain only information specific to a particular UH60A Black Hawk helicopter with a unique T700-GE-700 turboshaft engine.

The proposed overall structure of the reconfiguration expert system is shown in figure 2. It consists of (1) an inference engine, (2) a control system restructuring knowledge base and rule base, and (3) a controller tuning knowledge base and rule base. The control system restructurer is already partially implemented. An on-line controller-tuning expert system for a certain class of single-input single-output systems has been developed [9]. It uses the same inference engine as the reconfiguration expert system. Work is in progress to extend the tuning expert system to multi-input multi-output plants with various control strategies.

The knowledge base of the restructurable control system consists of information about the plant and its controller. 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 nonlinear characteristics. Information stored here can be updated in response to plant changes as new data about the system 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 variables to be given values by the inference engine during the discovery of new relationships.

A separate knowledge base exists for the tuning system. Following the approach of [9], it contains response characteristics associated with well-tuned loops of the type in question. It also has data on any previous responses obtained in the tuning process.

A rule base for a single-input-single-output controller tuning expert system has been created [9] and is in the process of being extended for multivariable controller tuning. The heuristics use the results from previous tuning efforts and other plant information for the next tuning attempt.

Figure 3 shows the interaction of the expert system with the overall system. A detectable change in the identified model of the plant will cause the expert system to restructure the controller to compensate for the alteration. After the new controller is implemented, the expert system will adjust the controller parameters to optimize the performance of the closed loop system.

SYSTEM CAPABILITIES

Figure 4 shows the anticipated setup of the overall system. It depicts a hierarchy with an expert system receiving information from a system identifier and a pattern extractor. This information is used in the restructuring and tuning 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 a Texas Instruments Explorer II+ LX. The system identifier is not yet implemented and the pattern extractor is not yet incorporated though it exists [9].

The objective of the system identifier is to provide an estimate of the system parameters on-line in real time. The plant, linearized about an operating point, can be modeled as

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

where x is the perturbation vector of state variables, u is the vector of control inputs, and y is the vector of system outputs. The matrices A, B, C, and D are the parameters returned by the identification routine. A detectable change in any of these causes the expert system to begin the redesign process.

The pattern extractor observes the transients as they occur and determines values for a set of features which fully describes the response. This set includes such attributes as percent overshoot, damping, and rise time. Each attribute is given a numerical value which is passed to the controller tuning expert system's knowledge base. If the values are too far from the desired, the tuning expert system is activated. Figure 5 contains a block diagram of this process.

Since an identification scheme is not currently implemented, the reconfiguration expert system uses a model of the plant directly from the simulation, i.e. there is perfect and immediate identification. 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 state continues to evolve.

The restructuring strategies that the expert system can currently use involve the pseudoinverse of B [4,5]. There are several limitations on the control mixer algorithm such as: it is applicable in cases where there is only actuator damage, it generally does not work well when changes in the system dynamics occur although an implemented modification to account for changes in the A matrix improves the results significantly in many cases; it cannot account for system nonlinearities; and it may produce excessive control commands [10].

For instance, consider an aircraft using state feedback as the control scheme. If an actuator sticks (which is equivalent to zeroing out a column of the B matrix), the expert system might take the realization (A,B,C) and manipulate it, using the Kalman Structure Theorem for instance, until it is minimal and B^TB has full rank. When the expert system achieves this goal, the pseudoinverse equation

$$K = (B^TB)^{-1}B^TB_0K_0$$

is used to determine the new controller matrix. Here B is the altered control matrix and B_0K_0 is the reduced order version of the state feedback matrix of the unimpaired full order model.

Examples of the heuristics used in the above example are:

1. if (A,B,C) is controllable and observable
   then *realization is minimal*
2. if B^TB 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 $A=A_0$ and
   $B \neq B_0$ and
   $C=C_0$
   then *control mixer scheme can be used*
5. if *pseudoinverse of B exists* and *realization is minimal* and *control mixer scheme can be used*
   then
   $K = (B^TB)^{-1}B^TB_0K_0$

where the italicized phrases represent assertions in the knowledge base and nonitalicized phrases indicate numerical tests or computations. These rules are typical of the heuristics contained in the rule base.

The control reconfiguration expert system employs a depth first search strategy. In this scheme, each appropriate redesign method is tried in turn until one produces a valid solution. The steps of the controller design algorithm are performed as long as the conditions for the methodology hold. If a step is infeasible, the algorithm is rejected and the next one is tried. If the rules differentiate sufficiently between the applicability of the redesign algorithms, the impractical ones should be eliminated early on in their execution so that the first method to be evaluated to any significant depth should produce a viable result.

The expert system executes only when invoked, for example when the control system needs to be redesigned. Once the system identification scheme is implemented, it will communicate with the expert system and cause it to start redesigning when a detectable change in the system matrices occurs.

CONCLUDING REMARKS

The expert system is able to handle a variety of reconfiguration situations. For the algorithms implemented thus far, the time it takes for the new controller to be designed and implemented depends upon the order of the system since matrix manipulations are involved almost exclusively.

The control restructuring algorithms which have been implemented so far handle most failure cases involving actuator damage (control mixer) and many situations where the system dynamics are altered as well (modified control mixer). Additional algorithms will be included to achieve a highly survivable system. The algorithms yet to be implemented are, in general, more complicated than the pseudoinverse-type and require more analysis during the control redesign. Therefore, their on-line implementation time is longer.

Some work has been done in the area of controller tuning by pattern recognition techniques for single-input single-output systems [9,11,12]. The methodology must be extended to multiple-input-multiple-output systems.

Currently the numerical calculations are performed in LISP. The mechanism is in place, however, to transfer these routines to the Explorer's LX processor (MC68020) in a language more suitable for number crunching [13]. This improvement will take the system a step closer to the goal of real-time operation.

Work is continuing on an on-line multiple-input-multiple-output system identifier [14]. Eventually it might be implemented on the LX processor or as a separate microprocessor-based system to signal the expert system if a detectable change occurs in the model.

An on-line pattern extractor which determines transient response features was developed in LISP and will have to be transferred to the LX or a separate microprocessor. It will pass the feature values to the knowledge base of the tuning expert system.

The simulation of a linearized T700 engine currently resides within the Explorer but a nonlinear, real-time model will eventually be implemented on an Applied Dynamics AD100 computer. A Black Hawk airframe simulation may be incorporated, too. At that point the interface between the two computers will allow for the full testing of the expert system in a more realistic situation.

This in-house effort is expected to illustrate the feasibility of using expert system technology for restructurable control and to demonstrate the benefit of possibly incorporating such a feature into the Army's helicopter fleet.

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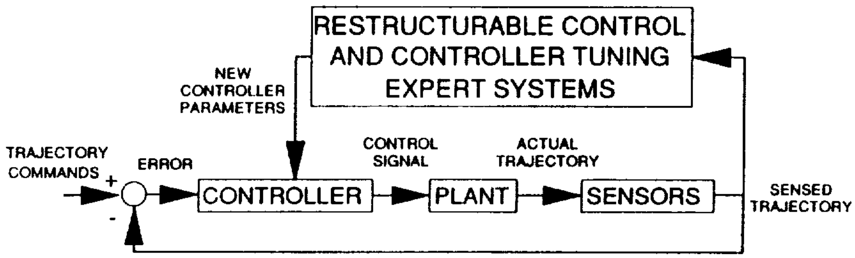

Figure 1. Block Diagram of the Restructurable Control System

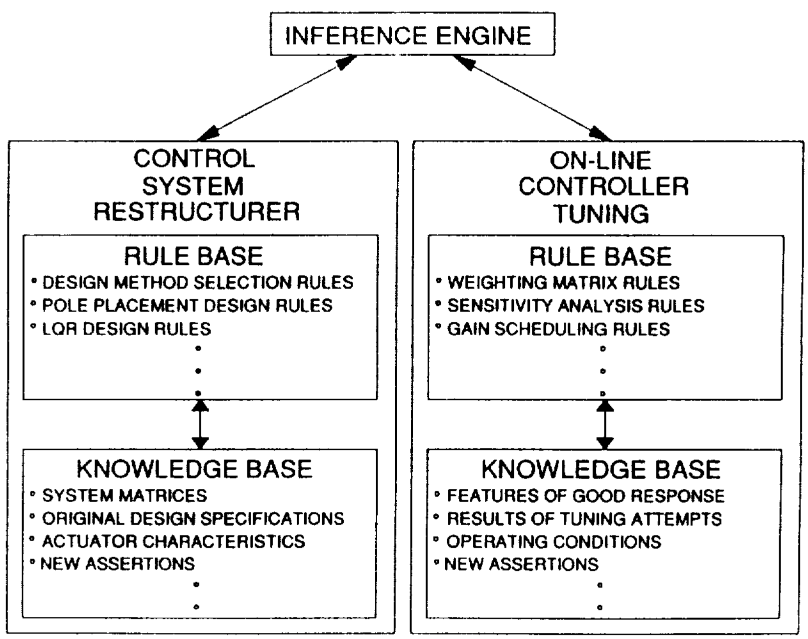

Figure 2. Structure of the Expert Systems

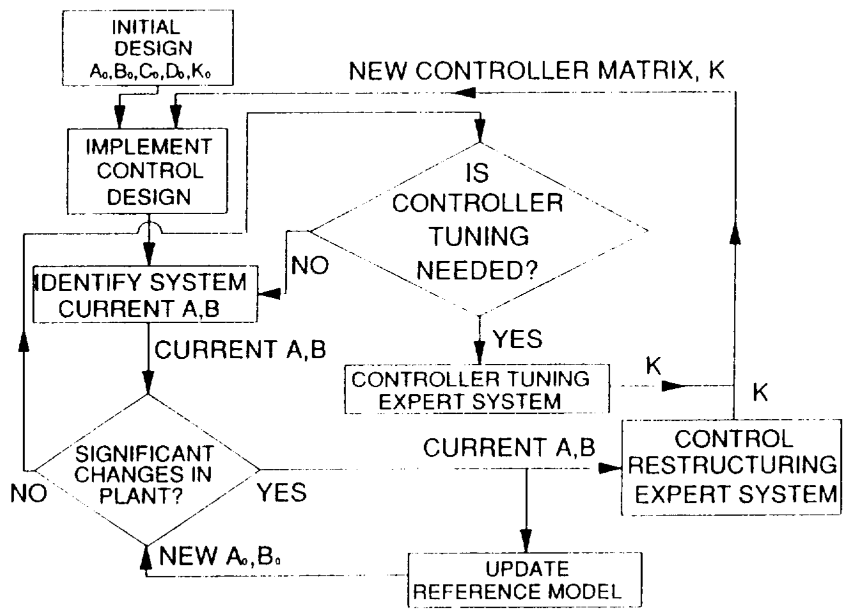

Figure 3. Expert System Interaction with Overall System

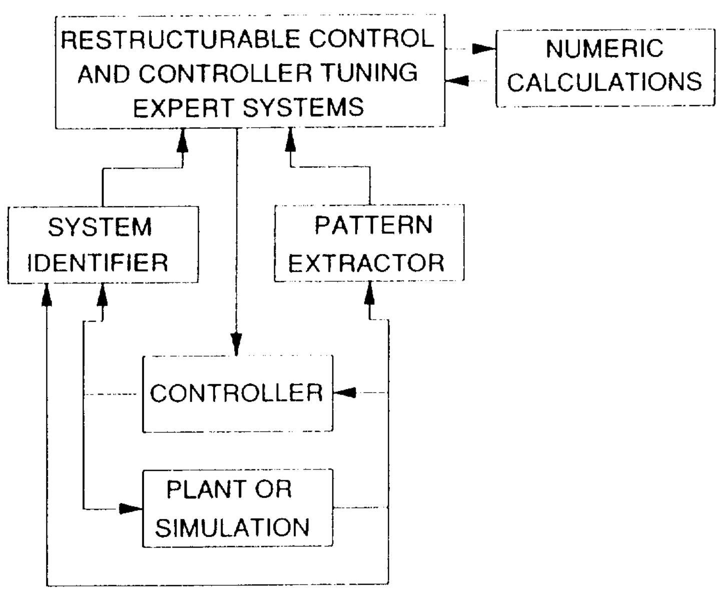

Figure 4. Overall Component Configuration

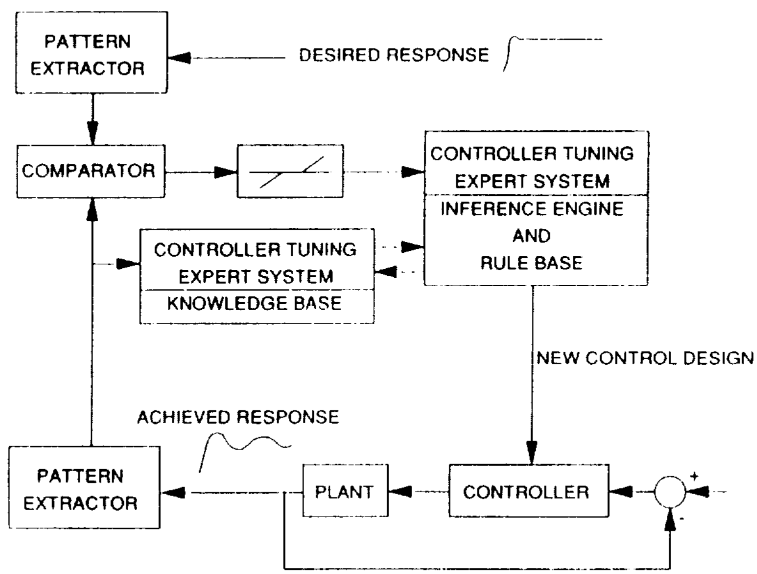

Figure 5. Controller Tuning Expert System

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16. Abstract

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