ROAD MAP TO ADAPTIVE OPTIMAL CONTROL

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Early application of full-authority digital controls to existing jet engines involved duplication of the existing hydromechanical control logic in digital form, and this provided little improvement in performance. Presently there are several different programs to apply digital controls to advanced variable-cycle engines (VCE's). DDA has already run the GMA 200 gas generator and the GMA 200 Joint Technology Demonstrator Engine (JTDE) under various levels of digital control employing digital logic designed specifically for digital control of these engines. In each case, the control was "optimized" according to a digital model of the engine, and the actual optimal performance varied from the design because of the modeling inaccuracies. This problem exists regardless of the design technique - classical, Riccati optimal gain, LQR, inverse Nyquist, etc. In general, the full potential of digital control for jet engines will not be realized until a adaptive, optimal propulsion system control is achieved that is capable of

(1) Integrated control of the propulsion system
(2) Active identification of the plant to be controlled in real time
(3) Real-time optimization of the control for the identified plant

This paper addresses an orderly, minimum-risk approach to achieving the latter two goals.

The mention of adaptive, optimal control reminds many of the past failures and special problems - especially stability - associated with adaptive controls. Thus, it is necessary to determine a systematic approach to the control development that displays an identifiable gain at each step in order to justify the additional complexity inherent in this system.

The major characteristic proposed here is a building-block control structure leading toward adaptive, optimal control. This approach simplifies the addition of new features and allows for easier checkout of the control by providing a baseline system for comparison. Also, it is possible to eliminate certain features that do not have payoff by being selective in the addition of new "building blocks" to be added to the baseline system.

This is achieved by beginning with a baseline control structure that is easily identifiable with present control systems. The configuration shown in figure 1 features an integrated propulsion system management feature that provides inputs to the engine control management section, like percent thrust required, inlet conditions, etc. The control management section selects the optimal gains, engine schedules, and control schedules for the control laws (classical speed governor, LQR, etc). The control laws issue control commands to minimize an error criterion within the control law. The control commands can be altered (generally limited) to protect the engine. The signal synthesis and estimation can be simple bandpass filters, Kalman filters, etc. Every digital control includes some degree of control diagnostics to provide mode selection (backup control when a failure occurs as a minimum).

The first step toward adaptive, optimal control is the identification of the plant or engine characteristics, along with the control diagnostics. This step is chosen first because it has payoffs outside the control. Of course engine diagnostics is a many-faceted objective. The philosophy suggested here is simply that engine diagnostics belongs in the control digital computer only to the extent that action is required by the control. This approach minimizes the potential dangers of increased cost, complexity, and weight and reduced reliability introduced by adding engine diagnostics. This must be balanced by the overall reduction in engine weight, cost, and complexity by sharing features between the control and engine diagnostics. Possible actions within the control are

(1) Lower gains
(2) Lower engine parameter upper limits
(3) Operating line moved further from surge for engine stability
(4) Alternative modes

However, most engine diagnostic techniques employed today are not accurate or sensitive enough to generally warrant such an interaction with control. Therefore we proceed one step further to parameter identification, as shown in Figure 2, to provide more diagnostics information and to lay the groundwork for adaptive control. Parameter identification techniques are being developed for both linear and nonlinear models, and the choice will depend mainly on the application. Generally a sequential technique will be employed to provide a real-time, on-line identification process. A filtered-sequential technique is currently favored at DDA because (1) it minimizes large transient effects, (2) it is less sensitive to noise, (3) it generates the required derivatives, and (4) it is well suited to slowly varying parameters that are compatible with current adaptive techniques. The results of parameter identification can be applied to

(1) Signal synthesis and estimation for the control
(2) Engine diagnostics
(3) Adaptive control

and this provides an identifiable payoff even if we fail in the next step - adaptive control.

We define an adaptive control as a control system that senses plant variations and adjusts control parameters to achieve a control objective. The ultimate goal is to provide a control system that continuously adjusts control parameters to achieve optimal engine performance. The term optimal is usually loosely used since it is often difficult to put exact physical significance on what is mathematically optimized to achieve the desired engine performance.

The next step toward adaptive control is to look at what control parameters one might adjust to achieve the desired control performance. The control gains generally only affect the transient behavior of the control, with only a secondary effect on steady-state performance for proportional control. Achieving true optimal gains would generally require an on-line solution to the

Riccati equation. Adjustment of the control schedules has a major influence on the steady-state performance and some effect on the transient behavior (acceleration and deceleration schedules). Here true optimal performance would require on-line optimization of the control schedules - generally a gradient search with multiple constraints. The control designer has little flexibility with the engine limits.

Now we have sensed engine variations and examined those control parameters we can adjust. But what about qualifying "desired engine performance" or "optimization" in this case. Off-line optimization is the most practical approach that can be achieved with today's technology. The steps to achieve this goal are

- Optimize nominal system
- Determine nonnominal models
- Optimize nonnominal systems
- Derive control parameter deviations from nominal
- Express control "trims" in terms of model deviations

The use of control trims reduces the authority of the adaptive process and provides a safe approach. With the development of on-line parameter identification this approach is feasible today.

However, one may wish to consider one further step - the ultimate goal, on-line optimization. This is a big step with many potential problems and must show sizable payoff to offset the risk and complexity. The most feasible approach is linear model optimization with a possible closed-form solution. However, the inaccuracies of the linear model may leave this approach less optimal than the off-line method using a nonlinear model.

On-line optimization of the nonlinear model does not seem practical with today's techniques - especially with the large number of constraints in the engine optimization problem. The on-line optimization of the actual engine through perturbation techniques creates even greater stability concerns. Before one rushes forward into on-line optimization, the potential problems of stability, high computational costs, large range of parameters, and transient effects must be weighed against the potential benefits of

(1) Better performance
(2) Simpler schedules
(3) Automatic failure modes

The final goal is an adaptive optimal propulsion control. The road is a difficult one with many pitfalls. The approach presented here will maximize the probability of success with a building-block structure that promises added payoffs at each step toward the final goal.

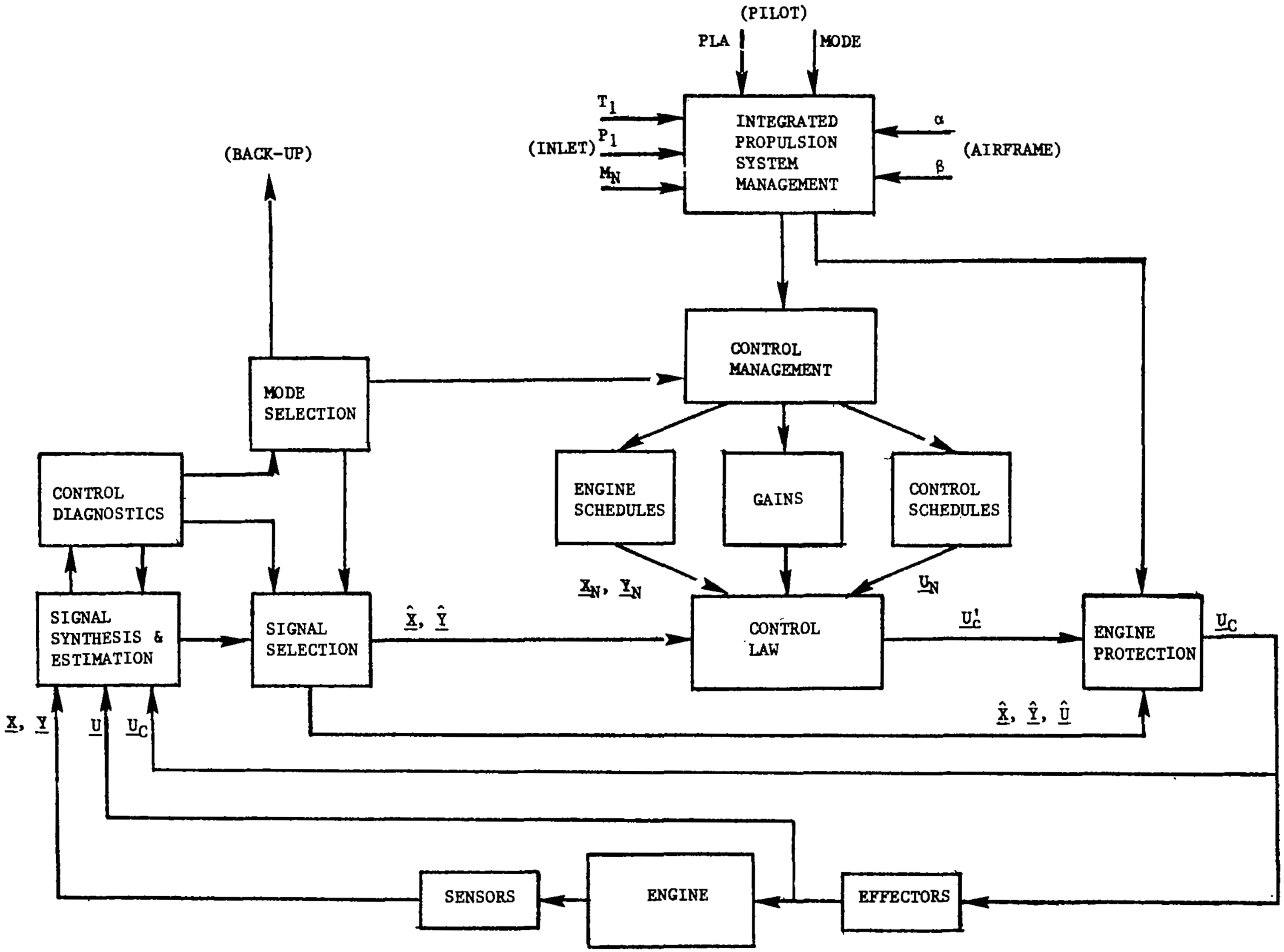

Figure 1. - Current control structure.

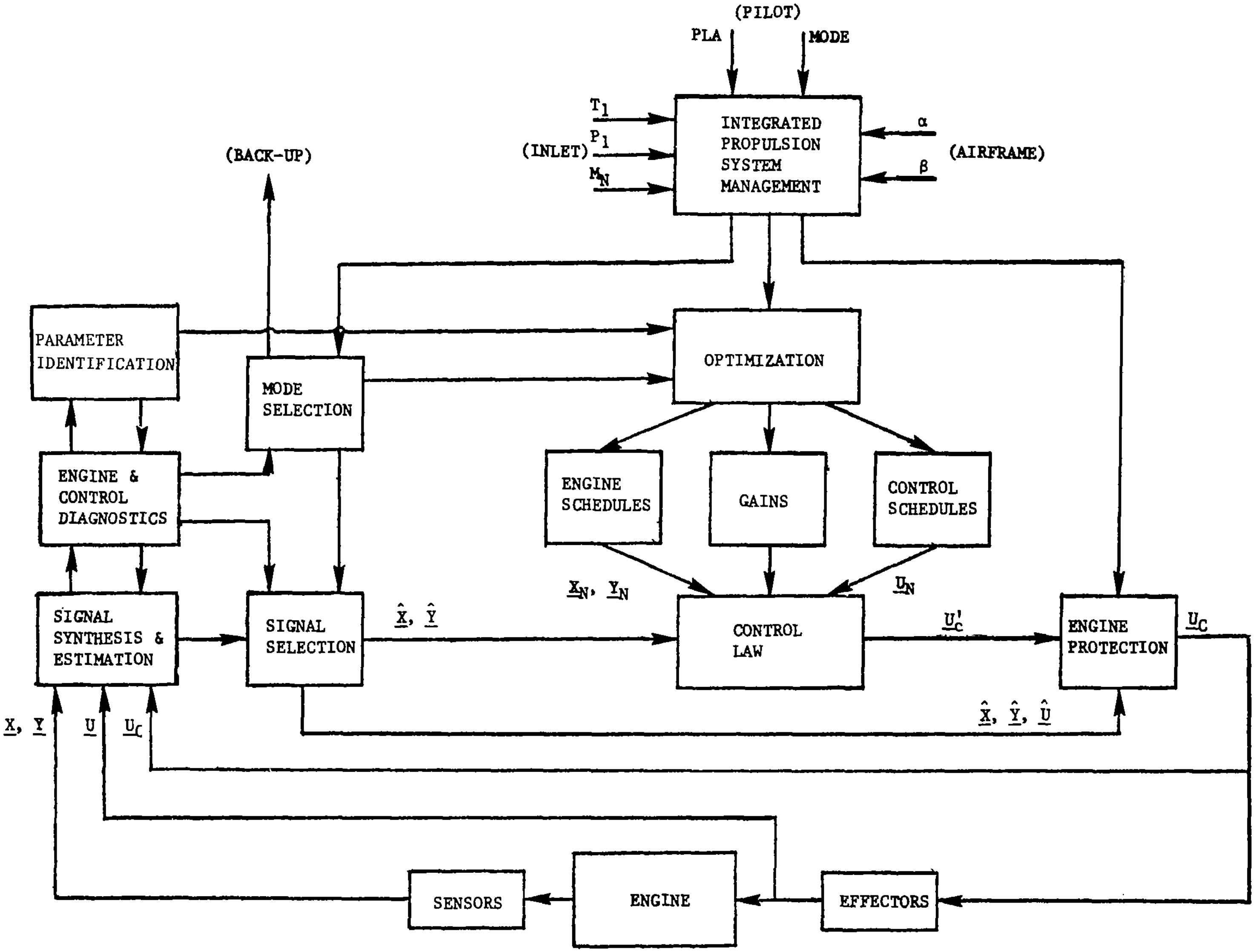

Figure 2. - Adaptive optimal control structure.