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FAULT-TOLERANT FLIGHT CONTROL SYSTEM COMBINING EXPERT SYSTEM AND ANALYTICAL REDUNDANCY CONCEPTS

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PROBLEM DEFINITION

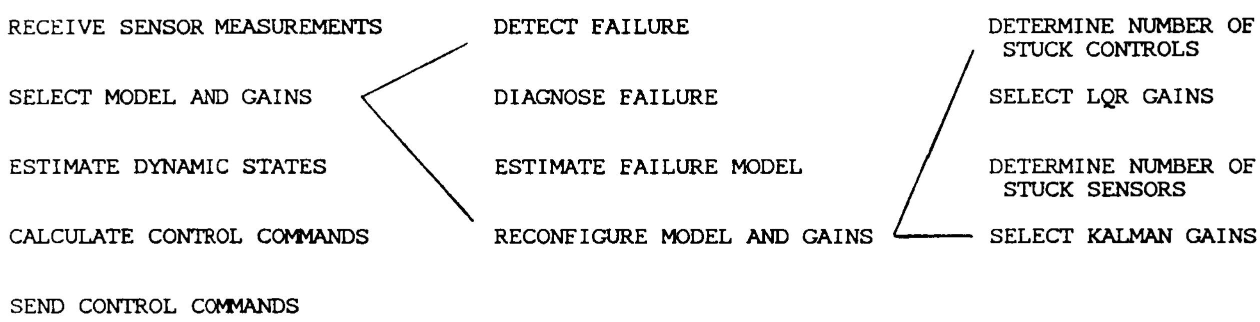
This research involves the development of a knowledge-based fault-tolerant flight control system. The objective is to design a control system capable of accommodating a wide range of time-critical aircraft failures, including actuator, sensor, and structural failures. A software architecture is presented that integrates quantitative analytical redundancy techniques and heuristic expert system problem-solving concepts for the purpose of in-flight, real-time failure accommodation.

The overall job of failure accommodation is broken down into five main tasks: executive control, failure detection, failure diagnosis, failure model estimation, and reconfiguration. The executive control task provides continual dynamic state estimation, feedback control calculations, and synchronization of the remaining tasks. The failure detection task monitors aircraft behavior and detects significant abnormalities. Failure diagnosis finds a list of aircraft components most likely to have caused the problem, while the failure model estimation task generates a mathematical model of the aircraft dynamics that reflects changes due to the failure. Finally, the reconfiguration task determines what action should be taken to correct the situation.

In order to carry out its assigned tasks, the control system uses as building blocks powerful analytical techniques developed within the state-space environment of modern control theory. For example, the executive control task employs a Kalman Filter and a Linear-Quadratic Regulator for estimation and control. Innovation-based and Multiple Model algorithms are used in failure detection and failure model estimation, respectively. Additionally, a weighted left pseudo-inverse procedure is available for reconfiguration if needed. These quantitative methods provide effective solutions to certain aspects of the failure accommodation problem.

Because they are computationally intensive, however, these algorithms must be used judiciously if real-time fault-tolerance ultimately is to be achieved. Efficient scheduling and selection of tasks and subtasks thus becomes an overriding control system design factor. Moreover, these quantitative algorithms do not reflect the type of problem solving performed by pilots. For these reasons, the control system will benefit from the incorporation of a qualitative, heuristic reasoning capability. The research described here uses artificial intelligence techniques to combine the strengths of quantitative and qualitative reasoning for fault-tolerant flight control.

FAILURE ACCOMMODATION TASK SAMPLE



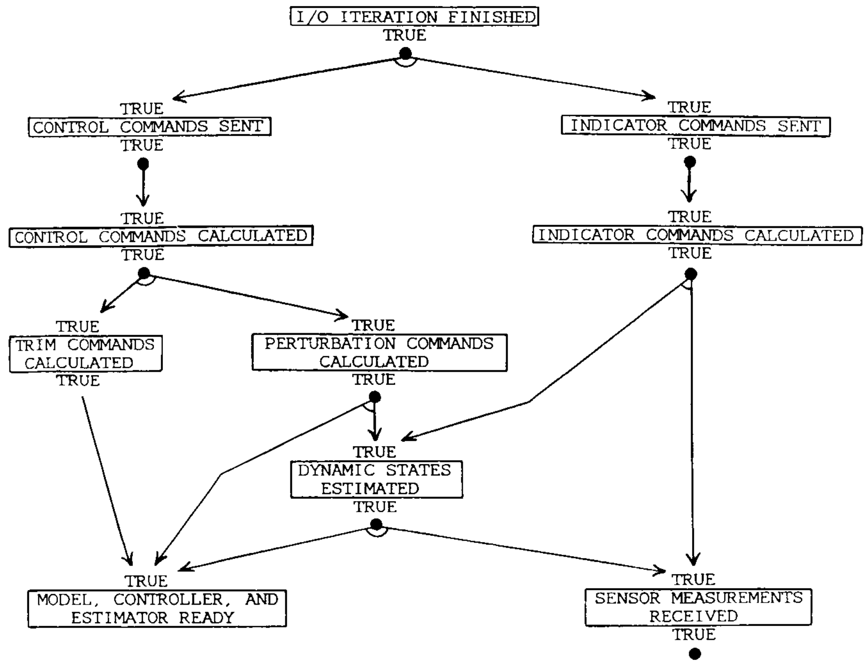
EXPERT SYSTEM DESCRIPTION

A rule-based backward-chaining expert systems approach is used to transform the problem of failure accommodation into a problem of search. The expert system is composed of a knowledge base and an inference engine. The knowledge base contains parameters that represent important variables and rules that relate parameters in the form of IF <PREMISE> THEN <ACTION> clauses.

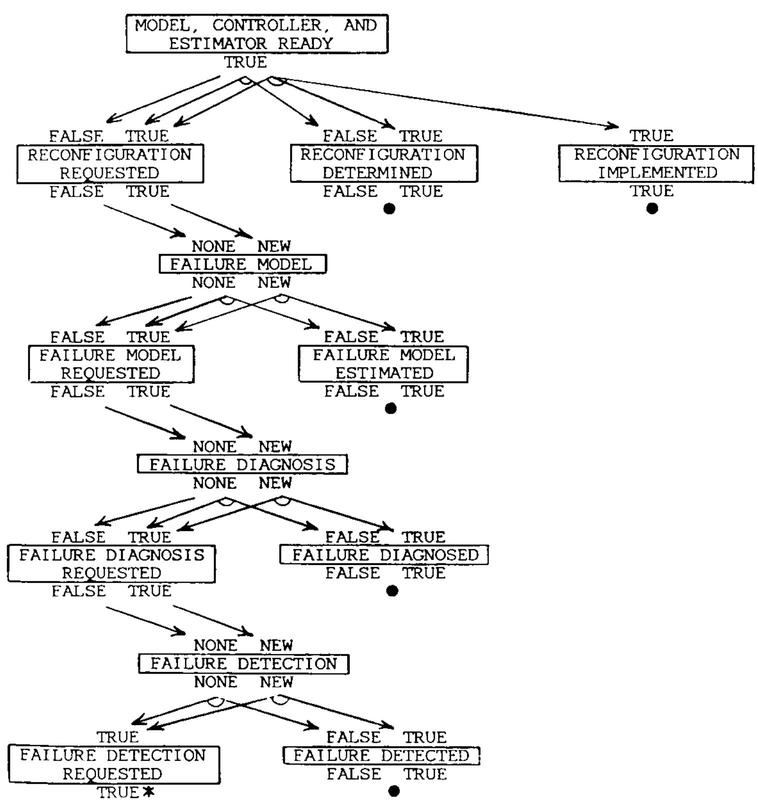
EXECUTIVE CONTROL KNOWLEDGE BASE SAMPLE

RULE-E02	IF	CONTROL COMMANDS ARE CALCULATED
	THEN	SEND CONTROL COMMANDS.
RULE-E04	IF	TRIM CONTROL COMMANDS ARE CALCULATED
		AND PERTURBATION CONTROL COMMANDS ARE CALCULATED
	THEN	CALCULATE CONTROL COMMANDS.
RULE-E07	IF	MODEL, CONTROLLER, AND ESTIMATOR ARE READY
		AND DYNAMIC STATES ARE ESTIMATED
	THEN	CALCULATE PERTURBATION CONTROL COMMANDS.
RULE-E08	IF	MODEL, CONTROLLER, AND ESTIMATOR ARE READY
		AND SENSOR MEASUREMENTS ARE RECEIVED
	THEN	ESTIMATE DYNAMIC STATES.
RULE-E09	IF	THIS RULE IS BEING TESTED
	THEN	RECEIVE SENSOR MEASUREMENTS.
RULE-E10	IF	RECONFIGURATION IS NOT REQUESTED
	THEN	MODEL, CONTROLLER, AND ESTIMATOR ARE READY.

EXECUTIVE CONTROL KNOWLEDGE BASE
(PART I)

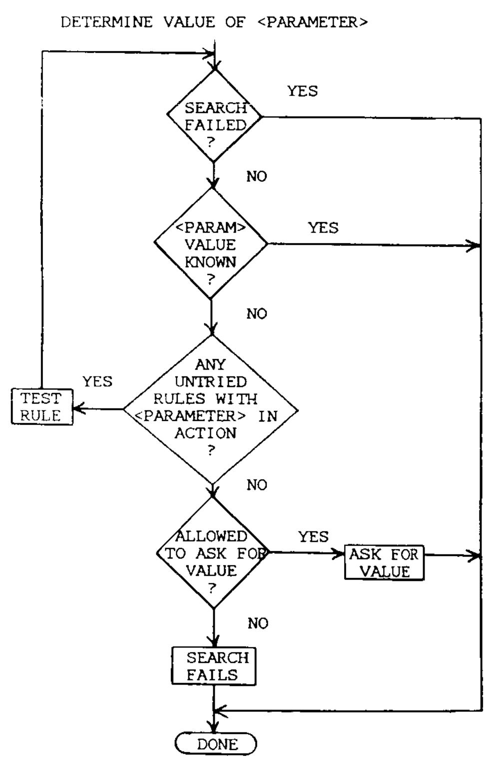


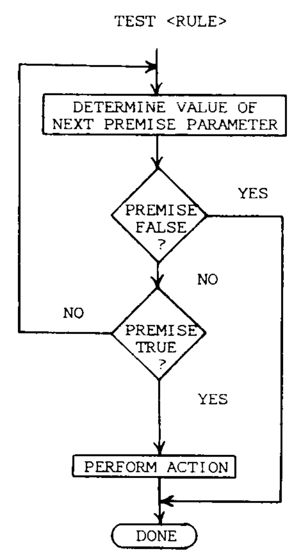
EXECUTIVE CONTROL KNOWLEDGE BASE
(PART II)



THE INFERENCE ENGINE

The inference engine applies a given set of rules to problem-specific data assigned to parameters. With all non-initialized parameter values assumed unknown, the act of trying to infer the value of a parameter, such as I/O-ITERATION-FINISHED, begins the search process. The estimation, control, and analytical redundancy algorithms reside as procedures in the actions of relevant rules, being executed when needed during the search. Presently, the knowledge base contains nearly 80 parameters and over 100 rules.

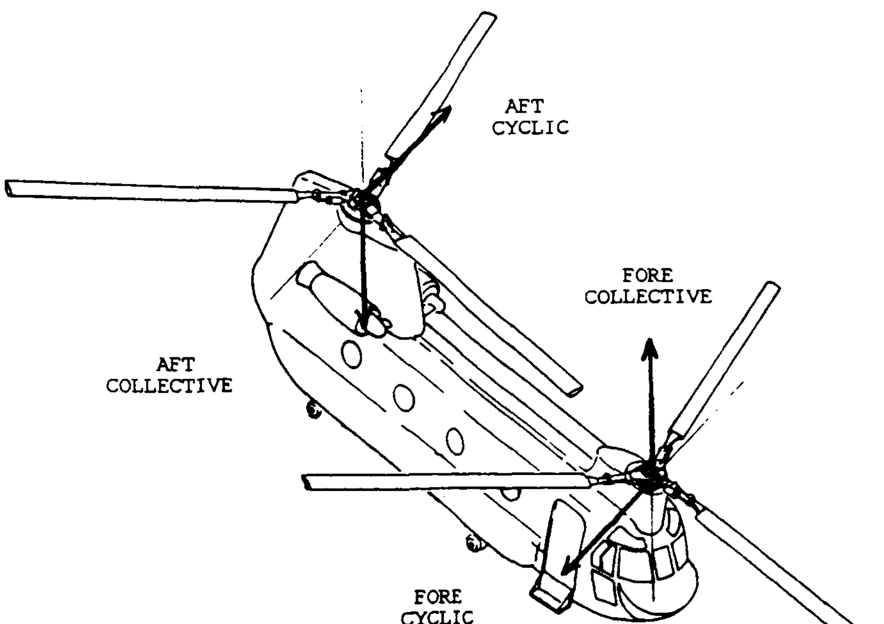




KNOWLEDGE BASE CONTENTS

TASK	PARAMETERS	RULES	MAJOR SUBTASKS
EXECUTIVE CONTROL	23	31	KALMAN FILTER LINEAR QUADRATIC REGULATOR
FAILURE DETECTION	8	12	NORMALIZED INNOVATIONS MONITOR
FAILURE DIAGNOSIS	2	1	SIGNAL DEPENDENCY SEARCH (TO BE INCLUDED)
FAILURE MODEL ESTIMATION	14	20	MULTIPLE MODEL ALGORITHM
RECONFIGURATION	31	37	LEFT PSEUDO-INVERSE

CH-47 CONTROL VECTOR DEFINITION



SIMULATION RESULTS

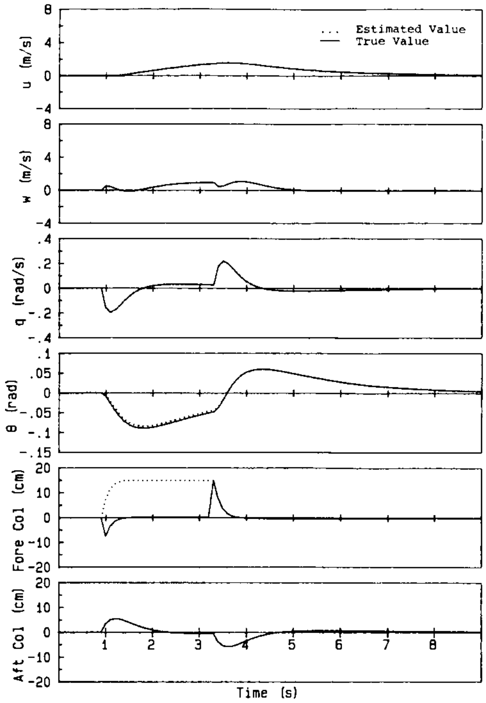
Control system performance is evaluated through ground-based simulations of in-flight failures. Using a linear discrete deterministic dynamic model of a Boeing CH-47 tandem-rotor helicopter, the effect of biased and stuck sensors and controls is investigated.

Failures are injected into the aircraft model at the 1.0 sec point of the simulation. When a sliding average of the nominal estimator normalized tracking error exceeds a preset threshold, the control system declares that a failure exists. Because rules for autonomous failure diagnosis and failure model hypothesis generation have yet to be included, the control system is given four failure model hypotheses at the end of time allotted for diagnosis. These hypotheses, to be used in the failure model estimation Multiple Model Algorithm, include the hypothesis representing no failure, the hypothesis representing the actual failure, and two hypotheses reflecting half and double the actual failure mode specification.

In order to simulate eventual parallel processing on a single-processor computer, the asynchronous tasks of failure diagnosis and reconfiguration are artificially delayed 0.5 sec each, thus simulating 0.5 sec task completion times. Executive control, failure detection, and failure model estimation, on the other hand, are all designed to cycle through one full search per sampling interval, and therefore incur no artificial delay.

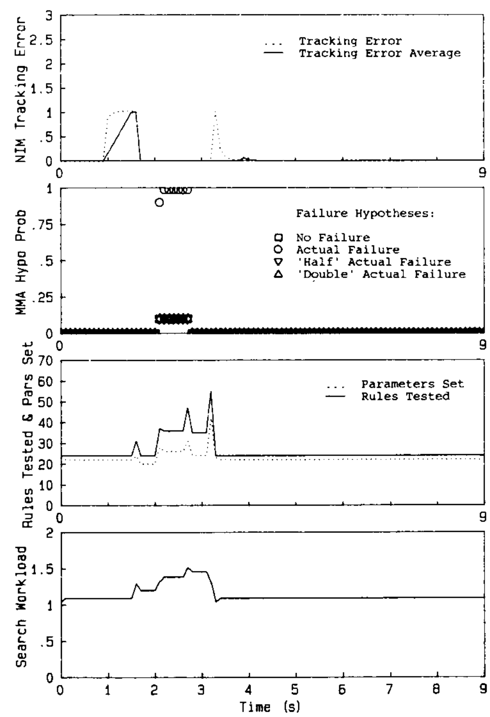
The scheduling and selection of quantitative tasks occurs inherently within the expert system search process. A measure of the amount of search effort required to accomplish this scheduling and selection is indicated by the number of rules tested versus the number of parameters set during the search. Prior to beginning the search, all parameters without an initial value are assumed unknown. Rules are tested in an effort to set parameters, ultimately setting the top-level goal parameter. With a normalized search <u>workload</u> defined as the number of rules tested divided by the number of parameters set, it can be seen that tasks stressing selection over scheduling incur a higher workload, representing a lower search efficiency.

SIMULATED ACCOMMODATION OF BIASED CONTROL: LONGITUDINAL STATE & CONTROL TIME HISTORIES



Forward Collective Pitch Control Biased 15 cm @ t=1.0s

SIMULATED ACCOMMODATION OF BIASED CONTROL: FAILURE DETECTION AND FAILURE MODEL ESTIMATION SEARCH RESULT TIME HISTORIES



Forward Collective Pitch Control Biased 15 cm @ t=1.0s

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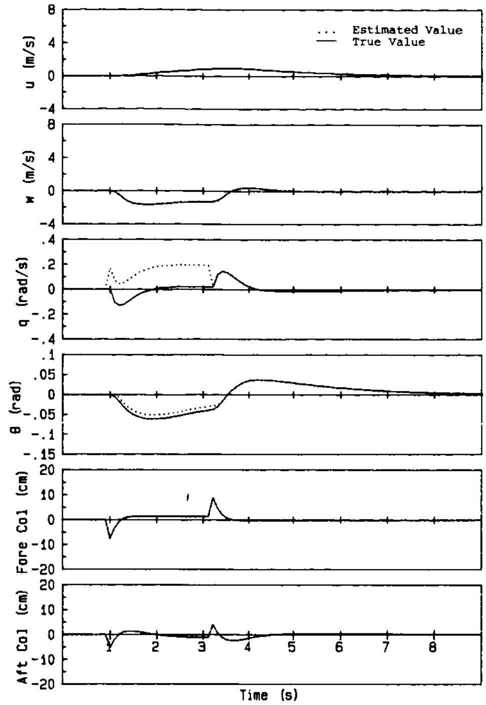
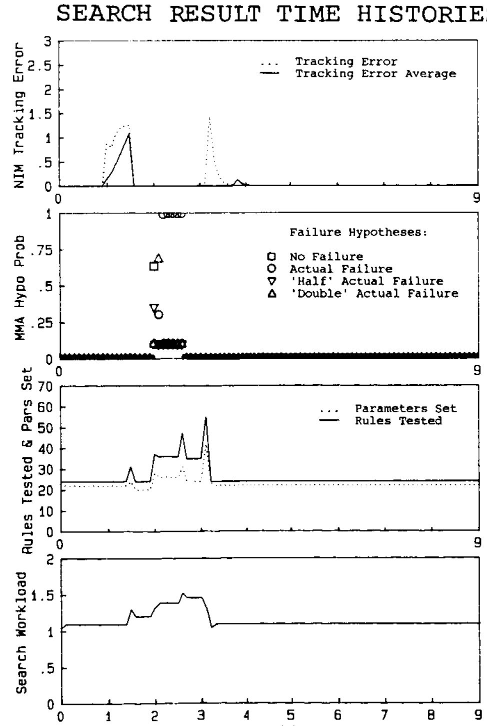
SIMULATED ACCOMMODATION OF BIASED SENSOR: LONGITUDINAL STATE & CONTROL TIME HISTORIES



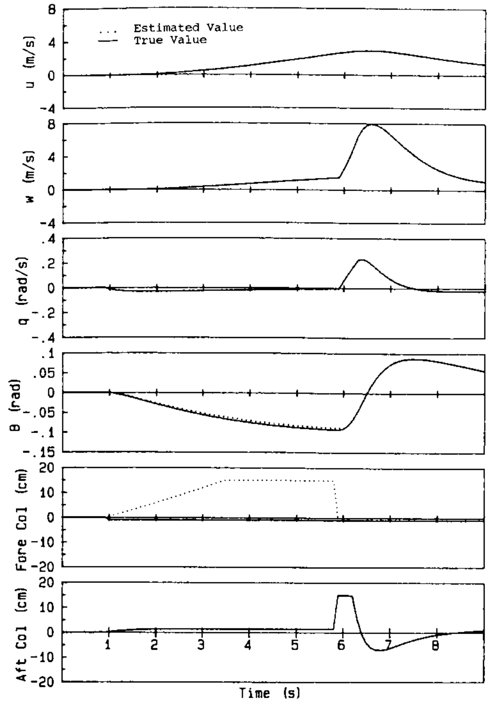
Pitch Rate Sensor Biased 0.18 rad/s @ t=1.0s

SIMULATED ACCOMMODATION OF BIASED SENSOR: FAILURE DETECTION & FAILURE MODEL ESTIMATION SEARCH RESULT TIME HISTORIES



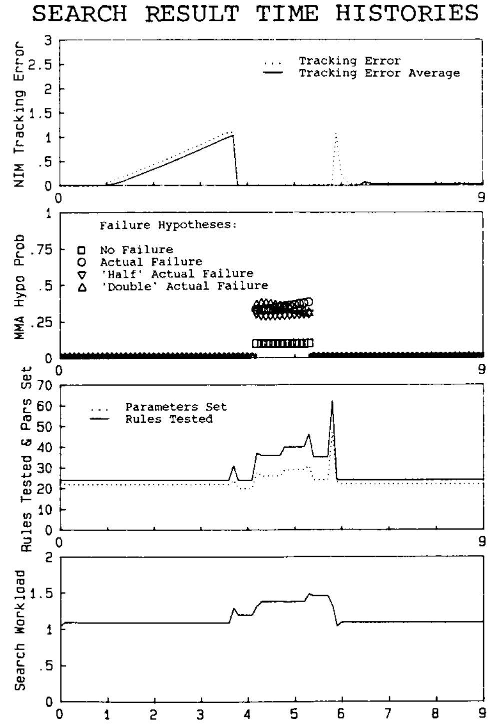
Pitch Rate Sensor Biased 0.18 rad/s @ t=1.0s

SIMULATED ACCOMMODATION OF STUCK CONTROL
LONGITUDINAL STATE & CONTROL TIME HISTORIES



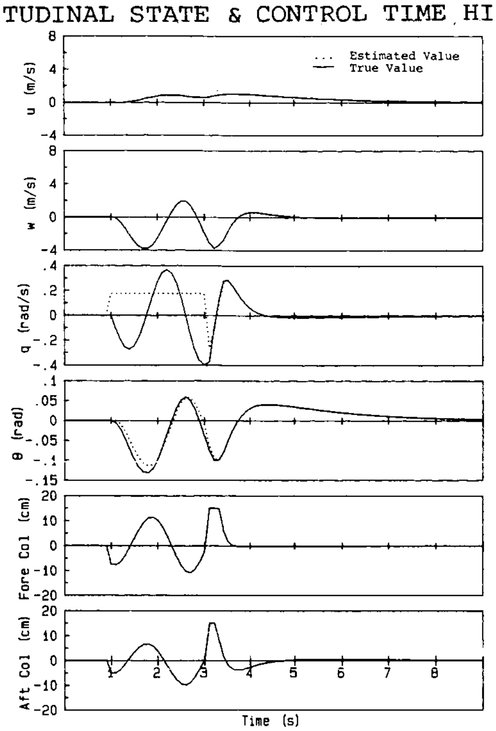
Forward Collective Pitch Control Stuck 1 cm from Nominal @ t=1.0s

SIMULATED ACCOMMODATION OF STUCK CONTROL:
FAILURE DETECTION & FAILURE MODEL ESTIMATION
SEARCH RESULT TIME HISTORIES



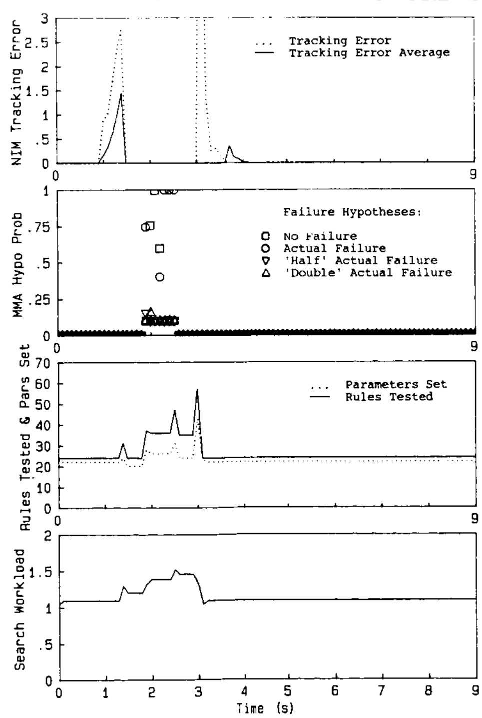
Forward Collective Pitch Control Stuck 1 cm from Nominal @ t=1.0s

SIMULATED ACCOMMODATION OF STUCK SENSOR:
LONGITUDINAL STATE & CONTROL TIME HISTORIES



Pitch Rate Sensor Stuck 0.18 rad/s from Nominal @ t=1.0s

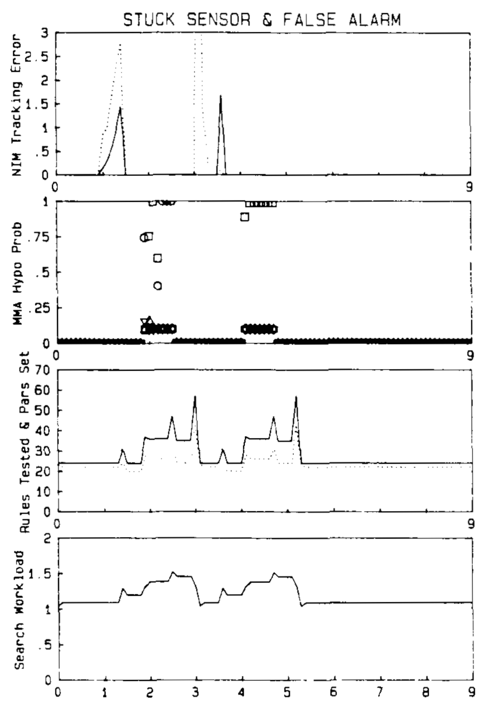
SIMULATED ACCOMMODATION OF STUCK SENSOR:
FAILURE DETECTION & FAILURE MODEL ESTIMATION
SEARCH RESULT TIME HISTORIES



Pitch Rate Sensor Stuck 0.18 rad/s from Nominal @ t=1.0s

RESPONSE TO FALSE ALARM

A failure detection mechanism should be sensitive to dynamic abnormalities, yet have a low false alarm rate. Should a false alarm occur, however, the control system must be able to recognize that a mistake has been made without compounding the problem. Simulations producing a false alarm immediately following reconfiguration for a stuck sensor demonstrate this ability in the proposed control system. By estimating the failure model to be the one corresponding to the no-failure hypothesis, the expert system recognizes the mistake and effectively suppresses any improper corrective action that might have otherwise taken place.



CONCLUSIONS

An expert systems approach to fault-tolerant flight control utilizing a rule-based backward-chaining search mechanism is an effective way to combine heuristic and analytical techniques. It allows the scheduling and selection of tasks to occur naturally within the action of rules, permits efficient flow of information between tasks, and allows the control system to be built incrementally.

Although at an early stage of development, the control system performs well and appears to provide an architecture suited to the difficult job of failure accommodation. The issues of failure diagnosis, parallel processing, and accommodation of additional failure modes are to be addressed next.

EXPERT SYSTEMS APPROACH ALLOWS

- NATURAL SCHEDULING AND SELECTION OF FAILURE-ACCOMMODATION TASKS
- EFFICIENT FLOW OF INFORMATION BETWEEN TASKS
- INCREMENTAL CONTROL SYSTEM GROWTH DURING DEVELOPMENT