AN EXPERT SYSTEM FOR WIND SHEAR AVOIDANCE

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ABSTRACT

Flight in strong wind shears, especially microbursts, poses a unique and severe hazard to aircraft. The disturbance caused by the wind field may literally exceed the performance characteristics of the aircraft, making safe transit impossible even with optimal guidance and control strategies. An unusual degree of piloting skill may be required to successfully elude danger. Only the best pilots may be able to cope with strong wind shears, but even they may be unable to safely penetrate extreme wind shears. Nevertheless, planes fly in moderate wind shear all the time; pilots learn to handle crosswinds, gustiness, and moderate frontal activity. The problem is that microbursts are random, rare phenomena: pilots do not develop the needed skills for coping with wind shear through normal experience. The typical pilot is likely to be confronted with a life-threatening wind shear only once or twice in an entire flying career; hence, it is unlikely that he or she can learn all the important signs of wind shear and maintain a high level of proficiency in the proper control procedures.

On-board computation provides an excellent opportunity to assist the pilot in surviving encounters with severe wind shears, but the logic that must be executed in real time is complex and must have sufficient inputs for framing decisions about appropriate control actions. The computer program(s) and hardware to perform this task must have attributes of expert systems and control systems, they must account for the limitations of aircraft performance, and they must operate in real time. At least as important as its technical specifications, the on-board system must provide a satisfactory interface with the flight crew, which bears the ultimate responsibility for assuring safety. This means not only that the system must deduce near-optimal strategies and tactics for emergency situations but that it must distinguish between truly hazardous conditions and the more likely alternatives associated with normal aircraft operations.

A program to investigate ways of protecting against the adverse effects of wind shear during aircraft takeoffs and landings has begun, with current emphasis on developing an expert system for wind shear avoidance. Our principal objectives are to

develop methods for assessing the likelihood of wind shear encounter (based on real-time information in the cockpit), for deciding what flight path to pursue (e.g., takeoff abort, landing go-around, or normal climbout or glide slope), and for using the aircraft's full potential for combating wind shear. This study requires the definition of both deterministic and statistical techniques for fusing internal and external information, for making "go/no-go" decisions, and for generating commands to the aircraft's autopilot and flight directors for both automatic and manually controlled flight.

The expert system for pilot aiding is based on the results of the FAA Windshear Training Aids Program, a two-volume manual that presents an overview, pilot guide, training program, and substantiating data provides guidelines for this initial development. The WindShear Safety Advisor expert system currently contains over 140 rules and is coded in the LISP programming language for implementation on a Symbolics 3670 LISP Machine.

BACKGROUND

Flight in strong wind shears, especially microbursts, poses a unique and severe hazard to aircraft. The disturbance caused by the wind field may literally exceed the performance characteristics of the aircraft, making safe transit impossible even with optimal guidance and control strategies. An unusual degree of piloting skill may be required to successfully elude danger. Nevertheless, planes fly in moderate wind shear all the time; pilots learn to handle crosswinds, gustiness, and moderate frontal activity. The problem is that microbursts are random, rare phenomena; pilots do not develop the needed skills for coping with wind shear through normal experience. The typical pilot is likely to be confronted with a life-threatening wind shear only once or twice during an entire flying career; hence, it is unlikely that he or she can learn all the important signs of wind shear and maintain a high level of proficiency in the proper control procedures.

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A program to investigate ways of protecting against wind shear has begun at Princeton University, with current emphasis on developing an expert system for wind shear avoidance. This program is sponsored by the NASA Langley Research Center under Grant No. NAG-1-384. Our principal objectives are to develop methods for assessing the likelihood of wind shear encounter (based on real-time information in the cockpit), for deciding what flight path to pursue (e.g., abort, go-around, normal climbout, or glide slope), and for using the aircraft's full potential to combat wind shear. This study requires the definition of deterministic and statistical techniques for fusing internal and external information, for making "go/no-go" decisions, and for generating commands to the aircraft's autopilot and flight directors in automatic and manually controlled flight.

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BACKGROUND

Hazards of Low-Altitude Wind Shear

Difficulty of Maintaining Pilot Proficiency

Proper Decision-Making and Control Strategy Enhances the Possibility of Avoidance and Survival

Meteorological Studies

Sensor Development

Flight Path Optimization

Reactive and Predictive Feedback Control

FAA Windshear Training Aid

FAA WINDSHEAR TRAINING AID

The FAA Windshear Training Aid was prepared with the support of the Integrated FAA Wind Shear Program. This two-volume manual was written by a team from the airframe industry that interacted with airlines, government, and academia. Principal results are expressed in a variety of ways for executive review, training classes, and public information. One principal goal is to identify the logical connections between pilot observations and pilot actions when wind shear is encountered. The functions that a jet transport aircraft crew should perform are summarized by a flow chart, as shown.

WINDSHEAR SAFETY ADVISOR

The WindShear Safety Advisor (WSA) is a computer program that uses concepts drawn from the world of artificial intelligence (AI) to assess the wind shear threat and to recommend safe piloting action. The current version is an interactive but non-real-time program for studying the input information and logic required to emulate and extend the FAA Windshear Training Aid to on-board computer systems. In particular, the WSA implements the stated rules of the Training Aid, and its development is uncovering the unstated (but critical) implications of the manual. The WSA currently does not address important human factors issues, such as presentation of information to the pilot and requests for pilot input or intervention, which would have little significance in non-real-time simulation. However, our goal is to identify a program structure that is appropriate for real-time use.

ISSUES in MONITORING and RISK ASSESSMENT

Situational Awareness

Reporting of Threat Indicators
Diversity of Information Sources
Relevance to Intended Flight Path
Multiple Reports of Same Phenomenon

Known Limitations to Target Parameter Selection

Runway length, obstacles
Aircraft performance
System malfunctions

Algorithms for Probability of Wind Shear Encounter

LOW plus MEDIUM = HIGH?
Bayesian Logic, Fuzzy Sets?

Admonishment of FAA Pilot Windshear Guide, page 36:

Use of Table 1 (Microburst Winsdshear Probability Guidelines) should not replace sound judgement in making avoidance decisions.

ISSUES in MONITORING and RISK ASSESSMENT

The FAA Windshear Training Aid is a significant achievement in the fight against the hazards of low-altitude wind shear; it identifies the major elements of observational meteorology that can be linked with dangerous wind shears, and it gives jet transport flight crews specific actions to take when wind shear encounter is unavoidable. Nevertheless, it takes a high level of piloting awareness and skill to evaluate the situation and to execute the implied actions correctly and quickly enough to avert catastrophe. To the extent that a computer can be fast and precise, it could assist the flight crew in this dangerous situation.

In seeking to build a computer aid for wind shear avoidance, it is necessary to model the implied logical patterns that the flight crew must use and to quantify subjective rules for computation. Many factors related to situational awareness, limitations to effective action, and efficient decision analysis must be considered, for the computer cannot exert "sound judgment " without having been programmed to do so.

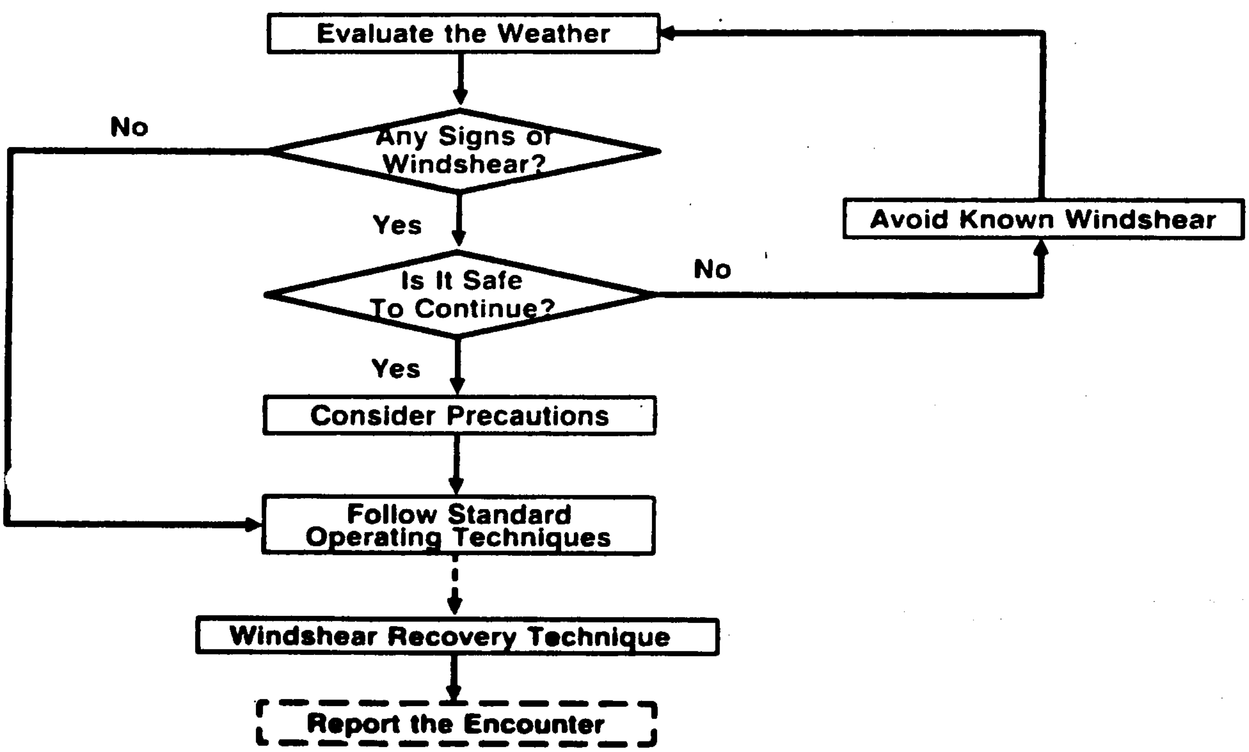
FAA WINDSHEAR TRAINING AID

One Result of the Integrated FAA Wind Shear Program Plan

Volume 1: Overview, Pilot Guide, and Training Program

Volume 2: Substantiating Data

Model of Flight Crew Actions



FAA WINDSHEAR TRAINING AID, continued

Flight crews are given information about the likelihood of dangerous wind shear when certain observations are made. If the probability of wind shear is LOW, standard procedures are recommended. If the probability is MEDIUM, the crew is instructed to consider precautions, including delay or alteration of terminal operations. If the probability is HIGH, delay or alteration of terminal operations is recommended, with specifics actions guided by flight phase. If more than observation suggests dangerous wind shear, the subjective probabilities should be added, although the guidelines for the risk assessment and the probability addition are imprecise. For example, two LOWs equal a MEDIUM, and either two MEDIUMs or a LOW and a MEDIUM equal a HIGH. There is no guidance regarding spatial or temporal characteristics of the observations; issues of proximity and degree of intensity are left to the pilot's judgment.

Although the strongest suggestion for piloting strategy is "avoid, avoid, avoid," recommended procedures for recovery or abort following wind shear encounter are given as functions of flight phase. These strategies are sub-optimal, but they materially enhance the probability of survival, in comparison to standard piloting procedures.

FAA WINDSHEAR TRAINING AID, continued

OBSERVATION	PROBABILITY OF WINDSHEAR
PRESENCE OF CONVECTIVE WEATHER NEAR INTENDED FLIGHT PATH:	
- With localized strong winds (Tower reports or observed blowing dust, rings of dust, tornado-like features, etc.)	HIGH
- With heavy precipitation (Observed or radar indications of contour, red or attenuation shadow)	HIGH
- With rainshower	MEDIUM
- With lightning	MEDIUM
- With virga	MEDIUM
- With moderate or greater turbulence (reported or radar indications)	MEDIUM
- With temperature/dew point spread between 30 and 50 degrees Fahrenheit	MEDIUM
ONBOARD WINDSHEAR DETECTION SYSTEM ALERT (Reported or observed)	HIGH
PIREP OF AIRSPEED LOSS OR GAIN:	
- 15 knots or greater	HIGH
- Less than 15 knots	MEDIUM
LLWAS ALERT/WIND VELOCITY CHANGE	
- 20 knots or greater	HIGH
- Less than 20 knots	MEDIUM
FORECAST OF CONVECTIVE WEATHER	LOW

After Liftoff/On Approach Windshear Recovery Technique

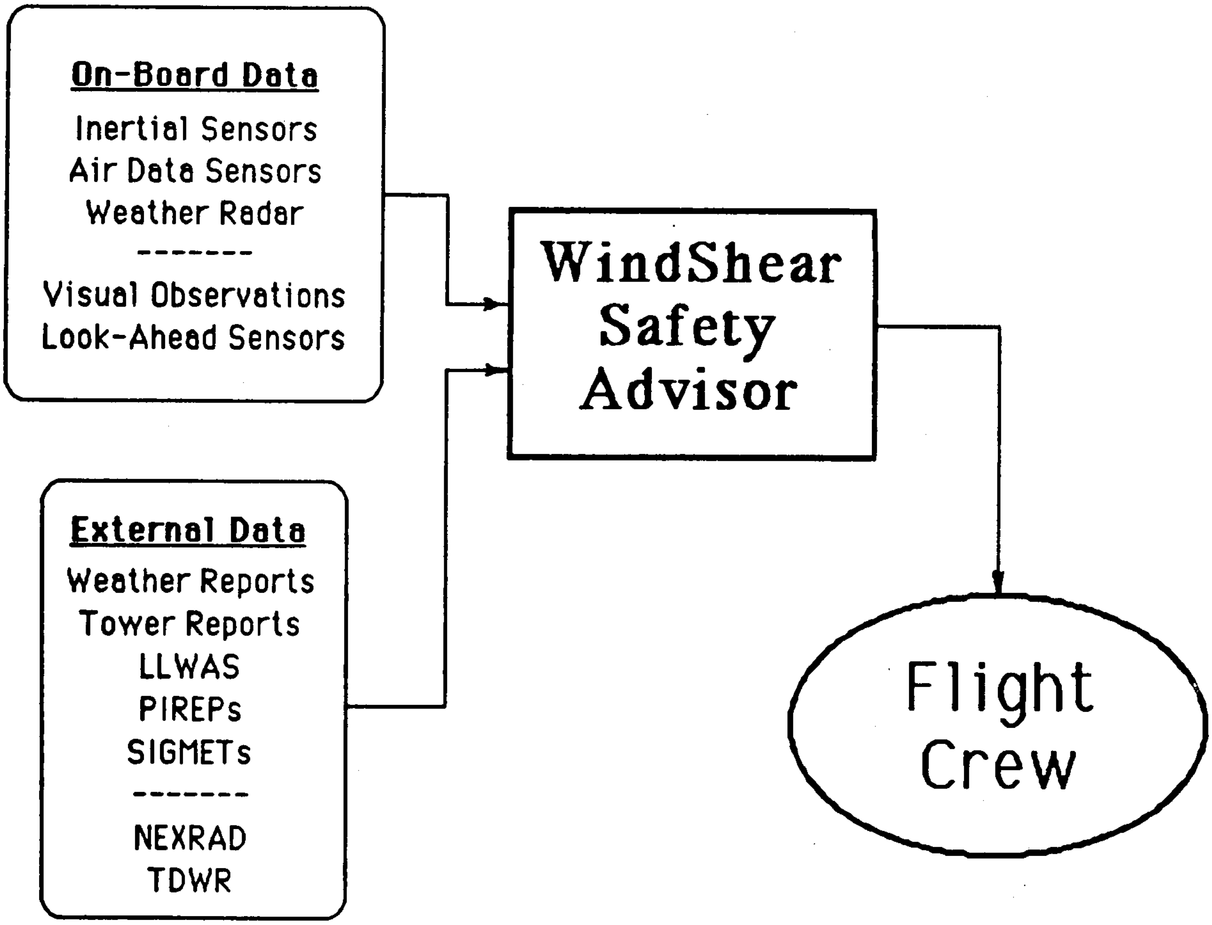
- THRUST
  - Apply necessary thrust
- PITCH
  - Adjust toward 15°
  - Increase beyond 15° if required to ensure acceptable flight path
  - Always respect stick shaker
- CONFIGURATION
  - Maintain existing configuration

WINDSHEAR SAFETY ADVISOR

FAA Windshear Training Aid

Expansion to Include Implications
and Data Input/Output

Cockpit Simulation



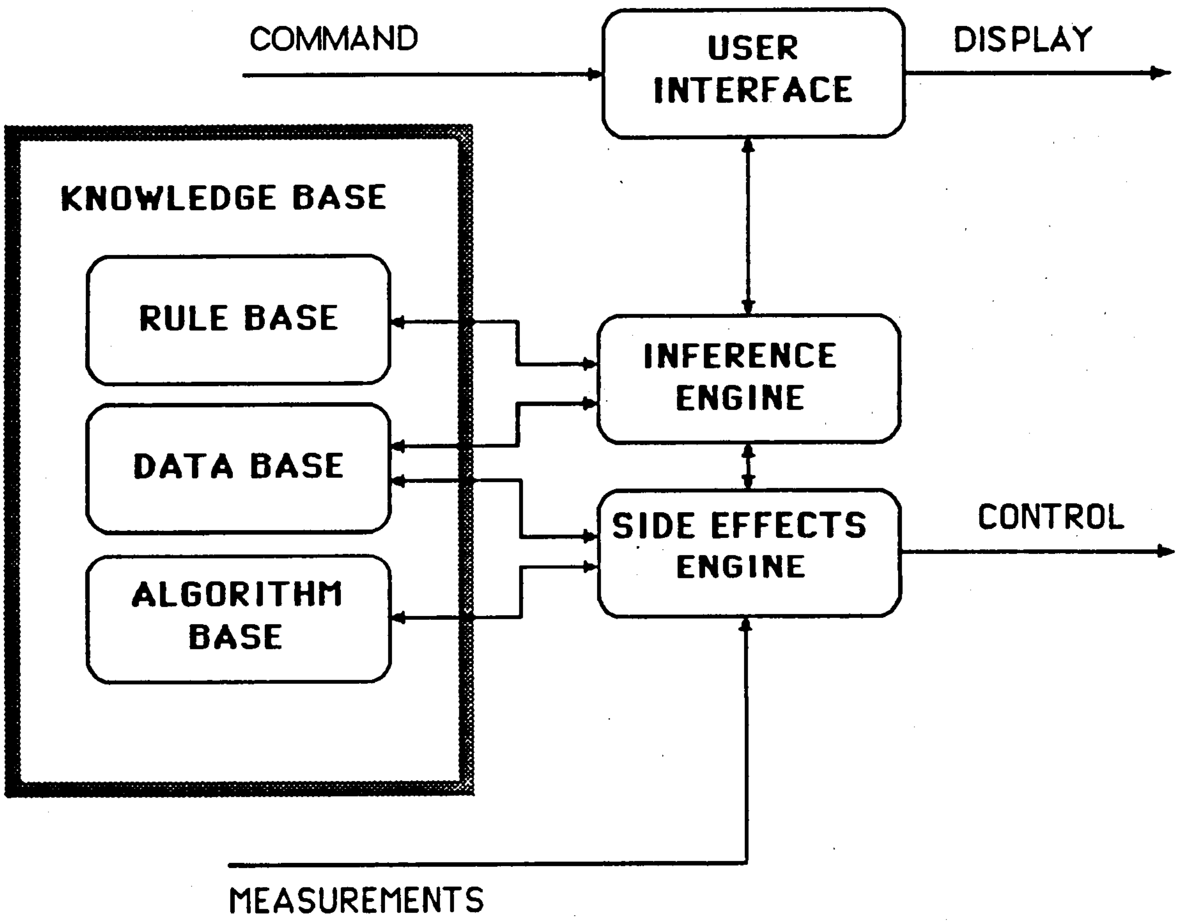
RULE-BASED SYSTEM for CONTROL

An on-board implementation of the WSA would be a Rule-Based Control (RBC) system having attributes of both expert systems and conventional controllers. In the parlance of AI, the Inference Engine executes the intelligence of the system, drawing on the Data Base for information (in the form of parameter values and properties) and on the Rule Base for logical relationships (in the form of IF...THEN or PREMISE...ACTION statements). In "firing" the rules, the Inference Engine may require that certain side tasks be accomplished, such as taking measurements, making estimates, computing control settings, and transferring commands to control effecters. Continuing the AI jargon, this procedural, quantitative computation is done in a Side Effects Engine that calls on both the Data Base and an Algorithm Base for its knowledge. (Measurement and control are considered side effects of the request for information and the decision-making process.)

Decision and control functions are readily separated in an RBC system, the former calling for symbolic computation, the latter for numeric computation. (In either case, the digital computer simply moves bits around; however, interpretations of the logical operations are different.) Not surprisingly, some computer programming languages are better than others at performing the two types of tasks, so it is most efficient to use different languages for decision and control during the development phase. For example, LISP is a good language for developing logical relationships among strings of symbolic data, while Pascal or FORTRAN is a good language for numerical computation. Consequently, LISP is the language of choice for current WSA development.

Once decision and control functions have been defined, they must be merged (in some sense) in the RBC system. It would be rare indeed for a given application to need all the subtle features of either development language; thus a single language can be used at the final step. Development of a real-time version of an RBC system is thus aided by one or more language translators that efficiently transform subsets of the development languages into the final code. Experience with current compilers and computers indicates that procedural languages like Pascal, FORTRAN, and C produce fast, concise target code for both decision and control.

RULE-BASED SYSTEM for CONTROL



Partitioning for
Decision and Control Functions

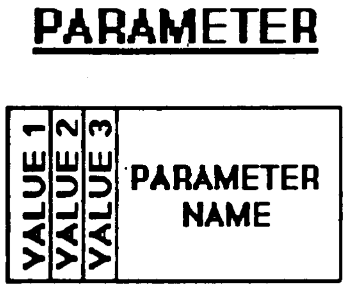
Integration of Symbolic and Numeric
Computation

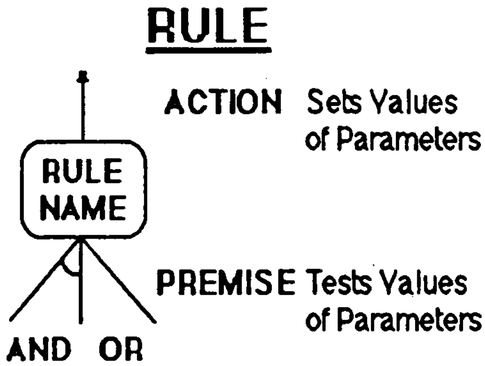
GRAPHICAL REPRESENTATION of KNOWLEDGE

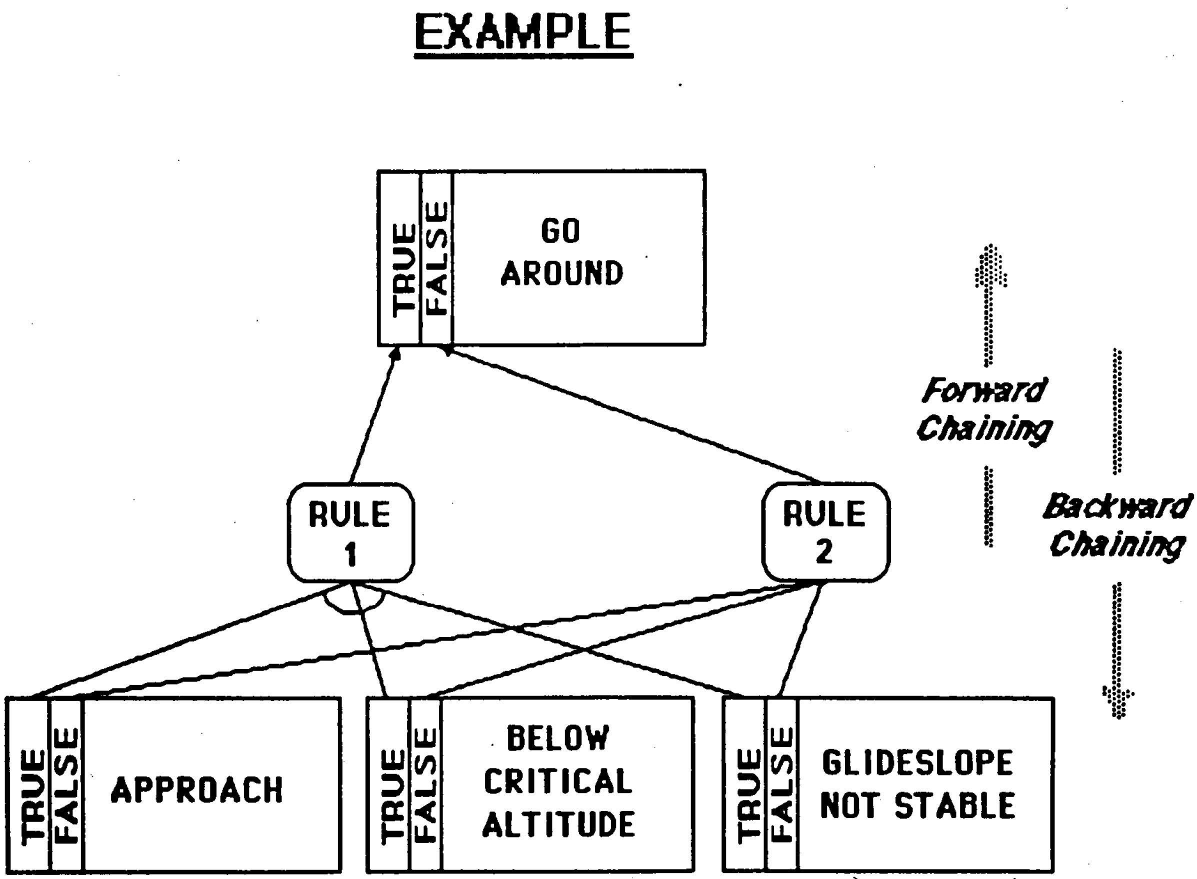
The elements of decision making needed for the WSA are illustrated by this simple example. A *parameter* is a quantity that can have several values as well as an array of complicated properties (not shown). A *rule* accepts one or more parameters as its *premise* and performs the *action* of setting another parameter if the values of its input parameters make the rule true. For the premise to be true, it may be necessary that *all* multiple parameters take certain values (represented by the arc between connecting lines), or it may be sufficient for *any* parameter to take a certain value (represented by no arc between channels into the rule).

The example shown illustrates such a rule: Rule 1 says that IF the flight phase is approach AND the aircraft is below a critical altitude AND a stable glideslope has not been established, THEN the pilot should perform a go-around. Rule 2 is the logical exclusion of Rule 1 and need not be implemented; it is here just for demonstration. Note that the go-around decision proceeds from the rule; in an array containing a number of such rules, setting parameters by moving from the bottom up is called *forward chaining*. Sometimes a result is known and it is necessary to determine what combination of parameters might have caused the result. Answering this question requires *backward chaining*, that is, moving through the rules from the top down. The WSA requires that both types of chaining be used at different times.

GRAPHICAL REPRESENTATION of KNOWLEDGE







STRUCTURE of a RULE

The current version of WSA defines each rule as a *list* in the computer language called Common LISP. Thus, each rule is expressed as follows:

(*name, premise, action, par-act, par-pre, translate*)

The meaning of each list element is defined on the chart. The Inference Engine effectively takes this list apart to find the needed inputs and outputs, performing an IF...THEN operation on the appropriate parts.

STRUCTURE of a RULE

NAME	Name of the Rule
PREMISE	Logical Relation of Parameters to be tested by the Rule
ACTION	Logical Result of Rule being TRUE
PAR-ACT	Parameters set by Action
PAR-PRE	Parameters tested in Premise
TRANSLATE	Documentation String for Optional Display

[Implemented as a Common LISP *LIST*]

RULE BASES of the WINDSHEAR SAFETY ADVISOR

The current WSA version contains over 140 rules that set over 80 parameters. They are organized in the left-to-right hierarchy shown, addressing the functions defined by the FAA Windshear Training Aid.

RULE BASES of the WINDSHEAR SAFETY ADVISOR

Executive

- Mission Phase
- Communication

Wind Shear Alert

- Wind Shear Detection
- Flight Path Deviation

Risk Assessment

- PIREP-LLWAS
- ATIS-SIGMET
- Generic Weather Risk
- Heavy Precipitation
- Rainshower
- Lightning
- Virga
- Turbulence

Action

- Standard Procedures
- Recovery Procedures
- Go-Around Procedures
- Delay Procedures

Planning

- Runway
- Airspeed
- Flaps

STRUCTURE of a PARAMETER

The parameters of the WSA currently are defined as Common LISP *variables*. There are different classes of parameters, defined by how and when their values are determined. A variable has the value *current*, to which is appended a *property list* containing (*use, update, expect, translate*), defined in the chart.

STRUCTURE of a PARAMETER

Parameter Classifications

INTERNAL	Parameter is internal to the Expert System; Value defined by a Goal-Directed Search
PRESET	Parameter is set by Initialization
STATE	Parameter is set by an Estimator
OUTSIDE	Parameter is set outside the Expert System

Parameter Properties

CURRENT	Current Value of the Parameter
USE	Rules that Use the Parameter
UPDATE	Rules that Set the Parameter
EXPECT	Allowable Values of the Parameter
TRANSLATE	Description of the Parameter for Optional Display

[Implemented as a Common LISP *VARIABLE*]

EXAMPLE PARAMETERS of the WINDSHEAR SAFETY ADVISOR

Names of some of the WSA parameters are shown and are, for the most part, self-explanatory. Each parameter may represent not only a symbolic or numerical value but a list that further defines its properties. Therefore, the Inference Engine can readily identify parameters that have certain attributes, in turn, aiding the searches associated with monitoring, assessment, planning, and action.

EXAMPLE PARAMETERS of the WINDSHEAR SAFETY ADVISOR

Communication Rule Base

New-information-received
Incident-reported
Tower-informed-goa
Tower-informed-delay
Precautions-taken

Flight Path Deviation Rule Base

Target-airspeed
Airspeed-deviation
Max-airspeed-deviation
Agl-at-max-speed-deviation
Target-vertical-speed
Vertical-speed-deviation

Outside Parameters

PIREP
LLWAS
Dispatch-office
ATIS
ASWW
SIGMET
Onboard-radar
Tower-report
TDWR
Wind-profiler

LABORATORY for CONTROL and AUTOMATION

Development of the WindShear Safety Advisor is being conducted within the Princeton University Department of Mechanical and Aerospace Engineering's Laboratory for Control and Automation. The laboratory has a broad variety of computational tools that are appropriate to research in artificial intelligence, computer-aided design, flight dynamics, and digital control. A real-time expert system for fault-tolerant control of a tandem-rotor helicopter has been implemented in the laboratory using three 80286 MULTIBUS computer boards for execution. Current WSA development makes use of the LISP Machine, which employs Common LISP for the expert system and FORTRAN for flight simulation.

LABORATORY for CONTROL and AUTOMATION

Symbolics 3670 LISP Machine

Silicon Graphics IRIS 3020 Workstation

Macintosh II

IBM PS-2/80

IBM PC-AT (2)

IBM PC/XT (2)

Lab-wide Ethernet Connection (TCP/IP)

Broadband Connection to IBM 3081s and $ETA^{10}s$

Portable and Fixed MULTIBUS Computers (5)

Fixed-Base Cockpit Simulator

DEVELOPMENT SCREEN for WINDSHEAR SAFETY ADVISOR

A typical LISP Machine display for WSA development is shown. The program developer uses a mouse to invoke features listed on the menu line and types information into the User Interaction Pane (or window). Parameters that change as a result of WSA activity are highlighted in the Parameter Information Pane, while the overall behavior of the expert system can be followed in the Result Monitoring Pane. This display is not intended as a prototype cockpit display but as an engineering tool for concept and program development.

DEVELOPMENT SCREEN
for
WINDSHEAR SAFETY ADVISOR

Princeton WindShear Safety Advisor Interface

Flight Plan Get Value Of Make Message Presets .... *(Menu Line)*

User Interaction Pane	Parameter Information Pane
• *Messages to program developer* • *Messages to crew, tower, etc.* • *Data and commands from program developer*	• *Parameters that have changed values* • *Other parameters of interest*

Result Monitoring Pane

- *Executive observations*
- *Monitored information*
- *Status assessment*
- *Planning activity*
- *Recommended action*
- *Current airport weather*

LISP Machine Implementation for Concept/Program Development

Interface to FORTRAN Flight Simulation

CONCLUSION

The WindShear Safety Advisor program implements the stated decision-making logic of the FAA Windshear Training Aid, as well as a set of unstated implications that are necessary for practical application. The WSA expert system contains over 140 rules that set over 80 parameters for terminal operations of jet transport aircraft. Future modifications will account for spatial and temporal variations of the aircraft and its meteorological environment, as well as for interfaces with the air traffic control system. The WindShear Safety Advisor sets the stage for cockpit simulation of logic for wind shear avoidance, which, in turn, will lead to practical systems for operational aircraft.

CONCLUSION

Logic of Wind Shear Avoidance

Computer Aiding for Crew Decisions

Spatial and Temporal Factors

Off-Line and On-Line Simulation

Interfaces with Sensors, Aircraft, and Crew