HELIX: An Application of Qualitative Physics to Diagnostics in Advanced Helicopters

Thomas P. Hamilton

Advanced Software Technologies
United Technologies Research Center
United Technologies Corporation
East Hartford, Connecticut 06108

Abstract: An expert system for diagnosing faults in the power train of a twin-engine gas turbine helicopter has been developed. The system, designated HELIX (HELicopter Integrated eXpert), performs diagnostic reasoning based on a hierarchical qualitative model representing the major power train components and the physical principles that govern their interaction. The approach represents a promising technique for automating the qualitative reasoning required to diagnose novel failures and may form the basis for extensive automation in an advanced cockpit configuration.

INTRODUCTION

Next-generation military helicopters will place significant demands on the pilot. Expanded mission requirements call for nap-of-the-earth flight, all-weather navigation, and air-to-air self-defense capabilities. In an effort to reduce weight and cost, a major goal is to perform these missions with a single pilot. To avoid overwhelming the pilot with information during difficult operations, extensive reliance on automation of difficult functions will be required.

An automated cockpit must be developed that takes the role of a pilot's assistant, possessing the ability to reason as an ensemble of experts [1]. Potential problems with traditional approaches to automating advanced cockpit functions include unacceptable performance due to system complexity, inability to handle novel situations that were not anticipated by system designers, and difficulties in integrating information from an array of automated subsystems [2]. The ideal automated cockpit must be able to interpret vast amounts of information from disparate sources in real time, integrate this information to form a coherent picture of the aircraft and its mission, take appropriate actions as required, and be able to explain the reasons for its actions in a manner that makes sense to the pilot.

Expert level performance has been achieved in a variety of domains using a rule-based production system approach (cf. [3]). As pointed out in [4], the rule-based approach is particularly well-suited to domains such as clinical medicine, where expertise is based on "compiled experience" acquired through exposure to a large number of examples. When new or unusual situations are encountered, however, rules of thumb representing an expert's compiled experience may not exist to cover the situation. To develop expert systems to handle novel problems requires the ability to reason from qualitative models of structure and function of devices [4]. The remainder of this paper describes an application of model-based reasoning to the problem of monitoring and diagnostics in advanced helicopters.

THE HELIX PROGRAM

A major goal in the HELIX (HELicopter Integrated eXpert system) project was the development of an experimental system for diagnostics that was capable of expert-level performance. To meet this goal, the system needed the abilities to 1) diagnose power train and sensor failures from sensor readings without modeling failure modes, 2) provide advice as to the appropriate response to the failure, and 3) explain the diagnosis, advice, and operation of the power train.

The approach used in HELIX integrates recent AI research from two areas. The first area is Qualitative Physics, which provides a general framework for representing and reasoning about the behavior of devices. As in [5-7], devices in HELIX are modeled as sets of "confluences", or qualitative differential equations. These confluences represent qualitative constraints on the variables that are associated with each component in a device. Constraint satisfaction and a qualitative mathematics are used to propagate the values of variables through the confluences and determine the legal states for a device. Using an expanded set of initial landmarks {-oo, 0 and +oo} [8-9], additional ordered landmarks between -oo and +oo may be added to allow reasoning about the relative magnitudes of qualitative values.

The second area of AI research HELIX draws upon is model-based diagnostics. Although restricted to the electronics domain, [10] describes a model-based system capable of diagnosing novel failures in digital electronic circuits. To deal with the complexity of devices, lazy instantiation of a hierarchical model representation is used. This enables reasoning to begin at the top of the hierarchy with the simplest model, and expands the substructure of a component only when more detail is needed. To diagnose failures without modeling the failure modes of a device's components, a process of constraint suspension is used. If, by temporarily suspending the constraints that define the normal behavior of a component, the behavior of the model is made consistent with observations, then a failure in that component is a valid hypothesis to account for the failure.

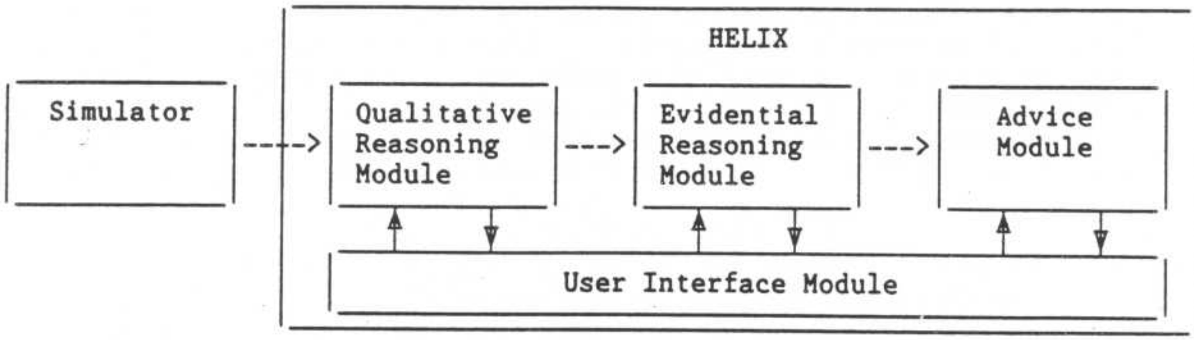
The HELIX program applies hierarchical reasoning techniques and constraint suspension to the more general representation of qualitative physics. The result is a general diagnostic reasoning system capable of isolating faults without modeling failure modes.

The Architecture of HELIX

To represent the operation of the engine and power train, a qualitative model composed of the major engine and power train components was developed. This model represents in a qualitative fashion the ways the components of the power train interact to power the aircraft. The inference procedures that use this qualitative model are based on a five-step process:

1) Generate Hypotheses: Infer possible causes for observations.
2) Accumulate Evidence: Find support for the hypotheses over time.
3) Make Diagnosis: Select the most plausible hypothesis.
4) Give Advice: Recommend appropriate actions.
5) Explain: Explain diagnosis and advice.

Fig 1. The HELIX Architecture



As seen in Fig. 1, HELIX incorporates these five processes in four modules: a Qualitative Reasoning Module, an Evidential Reasoning Module, an Advice Module, and a User Interface Module. Taking sensor data as inputs, the Qualitative Reasoning Module uses its qualitative model to evaluate the state of the power train. If sensor readings inconsistent with the model are detected, the Qualitative Reasoning module generates hypotheses to account for this abnormal behavior.

The results of the qualitative reasoning are passed to the Evidential Reasoning module, which evaluates the evidence as it is collected and updates the plausibility ratings of hypotheses. When sufficient evidence accumulates to confirm a diagnosis, the Evidential Reasoning Module sends the diagnosis to the Advice and User Interface modules. The Advice Module determines the appropriate actions to take given the diagnosis and other factors and sends the advice to the User Interface Module. The User Interface Module is responsible for displaying the diagnosis and advice in appropriate windows on the HELIX display screen as well as sending portions of this text to a voice synthesizer for speech output. The User Interface Module also interprets queries and accesses one of the three reasoning modules to determine an appropriate response.

HELIX was implemented in Common Lisp on a Symbolics Lisp Machine. HELIX makes extensive use of the Symbolics' high-resolution bitmapped monochrome display and windowing capabilities. Speech output is accomplished by a Digital Equipment Corporation DECtalk text-to-speech converter. Details of the four modules of the HELIX program follow.

Qualitative Reasoning Module

The Qualitative Reasoning module consists of five parts: a qualitative model, a model-building program, qualitative physics algorithms, diagnostics routines, and a memory component. The qualitative model describes the interrelationships between components of the engine. The model-building program builds the hierarchical model which is instantiable at any level of detail. The qualitative physics (QP) algorithms perform constraint propagation to determine legal states of the model and the transitions between legal states. The diagnostics routines use the QP algorithms to determine whether a set of gauge readings is consistent with the normal operation of the engine as described by the model. If a discrepancy exists between what the gauges read and what the model predicts, a hypothesis generation process is initiated. The memory component stores the results of qualitative reasoning.

Qualitative Model - In HELIX, the qualitative model is defined by a set of components and conduits. Each component may be viewed as a black box with a number of terminals representing inputs and outputs. The qualitative equations, or confluences, for a component specify the way the component acts upon the materials entering or leaving its terminals. Thus, the confluences act as constraints on the legal values of a component's terminals. Conduits are idealized connections between the terminals of different components and do not act on the materials passing through them. The confluences of the components together with the conduits that join them define the qualitative model of a device.

Model-Building Program - To make reasoning with the model more efficient, a hierarchical representation has been developed. A model-building program takes as inputs the components, conduits, and external terminals of a device. By solving the constraints of the components and conduits in terms of the external terminals, a high-level model of the device is created. This new model represents the interaction of the components using a reduced set of constraints. The model building process may be repeated to an arbitrary level to hierarchically represent the substructure of a complex device. A component library is maintained containing reusable models. A graphical interface to the model builder allows the user to select components from the model library and connect their terminals to construct new models.

The qualitative model of HELIX currently consists of four levels. In its most reduced form, the top-level helicopter model uses 151 constraints to model the interaction of 16 sensors and five pilot inputs. Dropping down a level in the hierarchy distinguishes five components of the helicopter model: flight controls, rotors, transmission, and the two engines. At the lowest level, 56 components are represented by 304 confluences and 132 conduits for a total of 436 constraints.

Qualitative Physics Algorithms - The qualitative physics algorithms operate on the qualitative model to perform two essential functions - constraint propagation and qualitative simulation. Constraint propagation determines the legal states for a model given zero or more known values by using an alternating cycle of constraint propagation and generate-and-test. Assuming an accurate model and error-free data, a component failure is detected when the envisioning algorithm fails to find any states consistent with the given inputs. Qualitative simulation determines the legal transitions between states. Although not used during diagnosis, qualitative simulation is useful for answering questions about the behavior of a device over time.

Diagnostics - To respond to unforeseen conditions that may occur during the operation of the helicopter, the ability to diagnose failures without modeling failure modes is required. In HELIX, only the normal behavior of a device is modeled. A component failure is then defined as any behavior that is inconsistent with the model of normal behavior. By systematically suspending the constraints of the components, it is possible to identify which components could, by behaving abnormally, account for the observations. This approach was suggested in [10] and has the advantage that failure modes need not be specified in advance. Thus, diagnosis of novel failures may be made.

When sensor data is received by the diagnostics component of the Qualitative Reasoning module, the constraint propagation algorithm of the QP component is used to determine if there is a discrepancy between the observations and the normal behavior specified by the model. If no state exists that is consistent with the constraints of the model and the observed sensor readings, the diagnostics component initiates the constraint suspension process to determine which constraints may have been violated by component failure. If, by removing the constraints of a component from the model, the observed behavior becomes consistent with the altered model, that component is a valid hypothesis.

Constraint suspension initially takes place with the highest level model. If a discrepancy exists between the observed values and the constraints of the high level model, a more detailed model is instantiated. The process continues recursively down the hierarchy, further isolating the problem until the problem is isolated at the component level. Using the hierarchy in this top-down fashion substantially reduces the number of constraints that must be considered in evaluating a hypothesis. A relatively small penalty is incurred instantiating the model at different levels of detail.

If the program is unable to determine any single component failure to account for the data, the program considers dual failures, then triple failures, and so on, until one or more hypotheses are determined which contain the minimal number of components whose simultaneous failure would account for the data. By exploiting the hierachical nature of the qualitative model, the HELIX program drastically reduces the complexity of diagnosing multiple failures. Rather than considering combinations of failures among more than 50 components, the program can restrict its attention to combinations of components in a branch of the hierarchy (approximately 5 components).

<u>Memory</u> - To further reduce processing, hypotheses generated for a discrepant state are stored in a memory component. If the current state has been processed before, the results are simply retrieved from memory to avoid regenerating the same hypotheses.

Evidential Reasoning Module

The need for an Evidential Reasoning module is spurred by two factors. First, models, by definition, are simplified representations of the actual device; hence, they may not contain all the detail necessary to correctly interpret given inputs. Second, the real-world data on which a model-based system must base its reasoning is often noisy. To overcome these obstacles, the Evidential Reasoning module combines evidence over time using the theory of evidence described in [11]. Every time a new set of hypotheses is made, measures of belief and plausibility are updated. The Evidential Reasoning module is responsible for combining the evidence to determine 1) the most likely hypotheses at any point in time and 2) when sufficient evidence has been acquired to make a diagnosis.

Advice Module

During and after the completion of the diagnosis process, the process of advising takes place. The Advice module contains a rule-based inference mechanism for determining appropriate actions to take given the sensor readings, flight regime, and diagnosis.

User Interface Module

After the diagnosis and advice have been given, explanation capabilities may be invoked to answer a variety of queries about the diagnosis, advice, qualitative model, and reasoning process. The user interface interprets the queries and accesses the appropriate reasoning modules to generate a response.

CONCLUSIONS

The HELIX program has been successfully tested on a variety of simulated failures, including failures in the lubrication system (oil pump), fuel system (governor, N2 control actuator, fuel pump), and various sensors. Diagnosing failures without modeling the failure characteristics has been achieved using the constraint suspension approach. Given an accurate model of the behavior of a device during normal operation, HELIX will thus be capable of diagnosing novel or unanticipated failures.

The hierarchical modeling and reasoning techniques in the current implementation provide an efficient means of isolating the source of a problem while examining the fewest constraints possible. Moreover, since multiple failures are combinatorial in the branching factor of the hierarchy rather than the number of leaf nodes, multiple simultaneous failures may be isolated in an efficient manner.

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