AUTOMATION OF CONDITION AND DETERIORATION SURVEYS USING KNOWLEDGE-BASED SIGNAL PROCESSING

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ABSTRACT

Condition and deterioration surveys using state-of-the-art sensory techniques generate far more data than can be interpreted by conventional methods. As a result, powerful sensory techniques such as ground penetrating radar and infrared thermography have yet to realize their full potential in civil engineering and construction applications. This paper proposes a method to automate the interpretation of large quantities of sensory data. This method combines conventional digital signal processing with encoded judgement and experience taken from the sensory, materials, and structural domains.

Automated radar data analysis to detect deterioration in reinforced concrete bridge decks has been selected as an illustrative example. In this application, a digital processor would produce a signature for each radar position based on the amplitudes and arrival times of radar waveform peaks. A knowledge-based processor would interpret these signatures using encoded knowledge of radar, concrete deterioration, and bridge engineering. The interpretation may conclude that deterioration is unlikely, that the environment is conducive for deterioration, and/or that deterioration has actually begun. Each conclusion would have an associated certainty factor. An analysis of several signatures has been carried out using mini-MYCIN for the knowledge-based processing. Mini-MYCIN is an expert system "shell" based on the MYCIN system developed for medical diagnosis. The signatures for each waveform were artificially generated to illustrate several conditions associated with deterioration.

We have concluded from this work that the Mini-MYCIN shell is not well-suited to spatial reasoning because of its context tree; nor is it well-suited to extensive data entry because of its interactive nature. We have also concluded that future work should seek to keep knowledge from different domains (e.g., radar, concrete, bridges) separate in the knowledge base. A better rationale for assigning certainty factors should also be developed.

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1. Introduction

The growing demands of managing and maintaining our aging infrastructural systems have added a new dimension to the need for in-situ condition and deterioration data. The availability of accurate and comprehensive condition and deterioration data is becoming increasingly important to a number of aspects of facilities management, including: planning future maintenance expenditures and associated financing; deterrence of deterioration using low cost pre-emptive measures; developing a rationale for prioritizing multiple repair and rehabilitation projects; and minimizing cost overruns by accurately specifying the required type and extent of maintenance. The demand for this data is common to all infrastructure systems (e.g. water supply, transportation, and waste disposal and treatment) and their associated elements (e.g. buried pipelines, tunnels, dams, pavements, bridges, and track).

A number of sensory techniques have been developed over the years which have the potential for meeting this growing demand. These include ground penetrating radar, infrared thermography, and electromagnetic conductivity. Such techniques bring powerful measurement potential to construction and civil engineering applications, a potential which has yet to be fully realized. One reason is that far more data is generated by these techniques than can be interpreted manually. The sensory data itself usually contains a large quantity of useful information which is often processed away to facilitate manual interpretation. In addition, condition and deterioration surveys, by their nature, require a large quantity of data, since the structures under analysis are extensive.

In order to extend the potential value of existing sensory techniques, we propose a method to automate the interpretation of large quantities of sensory data. With such a method, data simplification required for manual interpretation can be eliminated, thus preserving the full content of the sensory data. Furthermore, sensory data taken over large areas or distances can be interpreted without time-consuming, costly, and tedious analysis. The proposed method achieves this automation by combining knowledge-based signal interpretation with traditional digital signal processing. The knowledge-based processor automates the application of encoded knowledge from the sensory, materials, and structural domains.

In order to develop this concept, we have selected the problem of bridge deck evaluation as a representative example. This example was chosen because it is one of national significance, there has been extensive research into the problem, and there are sensory technologies which show potential for rapid surveying of condition and deterioration.

2. Background

Most of the five hundred thousand highway bridges and elevated roadways in the United States have reinforced concrete deck slabs. In northern climates where de-icing salts are used, salt permeates the concrete and corrodes the reinforcing bars. Corrosion causes the steel to expand, which, in turn, causes the concrete to crack. These cracks may connect from bar to bar to form a planar "delamination," which ultimately leads to spalling of the road surface (6).*

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*Numbers in parentheses refer to references listed in the bibliography.

Since this is a subsurface problem, it is not clearly recognized until the roadway starts to spall. Bridge maintenance engineers would like to detect deterioration, quantify its severity, and determine its geometric boundaries well before spalling begins (5). Such information would enable them to plan and budget future maintenance, to implement preemptive measures, and to determine the extent of a specific repair project. Each of these applications uses condition data with different levels of detail and different degrees of certainty.

Existing techniques for detecting "delamination" deterioration employ acoustic sources which produce a "dull" sound where the concrete is cracked, and a high pitched "solid" sound where the concrete is not cracked (6). Since these techniques are very slow, there has been interest in automating the use of ground penetrating radar as an alternative technique for detecting deterioration (3, 4, 5, 9). Radar is a non-contact technique which can be implemented at high speed. Radar responds to several conditions associated with deterioration and cracking, but not to cracking directly. These associated conditions can be identified by a radar analyst, but their combined significance must be interpreted by a concrete deterioration specialist and a bridge engineer. In addition, the typical radar scan removes many details of the waveform in order to produce an easily interpreted 2-D graphic representation. Much of the information required to identify the above-mentioned associated conditions is lost in the production of conventional radar traces.

The overall objective of this project is to automate the radar signal interpretation in a manner which: (1) retains the deterioration-related elements of the signal, and (2) utilizes the experience and judgment of the radar analyst, the concrete deterioration specialist, and the bridge maintenance engineer. The ultimate goal would be a system receiving a digitized radar waveform as its primary input, and producing natural language statements describing the bridge deck's state of deterioration at each location as output. The "user" (a bridge maintenance engineer) would supply structural data obtained from "as-built" drawings, along with data related to the measurement environment (temperature, recent rainfall, etc.). This user-supplied information would be incorporated into digital signal processing algorithms and into rules for interpreting the processed signals.

Our first step in pursuing this overall objective has been to structure a knowledge base and apply it to fabricated waveform signatures using an available expert system "shell." This effort will be further described in Section 4.

3. <u>Structure of the Problem</u>

Bridge decks are constructed of reinforced concrete and serve both as the load carrying member for vehicular wheel loads, and as the wearing surface. They contain top and bottom layers of reinforcing bars ("rebar"), with each layer containing equally-spaced bars in both longitudinal and transverse directions. Bridge deck deterioration occurs primarly between the top surface and the top layer of rebar, due to corrosion of the top rebar. It is known that the thickness of concrete over the top rebar ("cover") is strongly correlated with the development of deterioration; i.e., thin cover (less than 1.5") results in rapid deterioration, and the deterioration slows with increasing cover thickness (6). It is also known that corrosion is associated with high conductivity in the concrete cover; corrosion products migrate through the concrete away from the corroding rebar; and corrosion products and chloride accumulate within the cracks created by the rebar corrosion (6).

Radar transmits electromagnetic pulses which travel through a dielectric medium, are reflected and refracted at interfaces representing changes in electrical properties, and are returned to an antenna (usually at the same location as the transmitter) (2). The time series of the reflected pulse returns constitutes the radar waveform. The velocity and attenuation of the radar return pulses are measures of the electrical permittivity and the conductivity of the materials through which the pulse has propagated. Materials with low permittivity and conductivity (e.g. air) produce high velocities and low attenuations. Materials with high permittivity and conductivity (e.g. salt water) produce low velocities and high attenuations. Deterioration in bridge decks can be related to rebar cover, chloride content, electrical conductivity, and anomalous concentrations of moisture (in cracks), all of which influence the radar waveform (2, 6).

In applying radar to concrete bridge decks, we expect at every location to obtain return signals from the top surface of the deck, the first layer of rebar, the second layer of rebar, and the bottom surface. Figure 1 shows a radar waveform produced in response to the pictured bridge deck cross section when the radar antenna is directly above the rebar. This waveform has been idealized by assuming that successive return pulses do not overlap. By looking at the arrival times and amplitudes of selected peaks in this waveform, we can infer the potential for, and actual progress of, deterioration in the bridge deck.

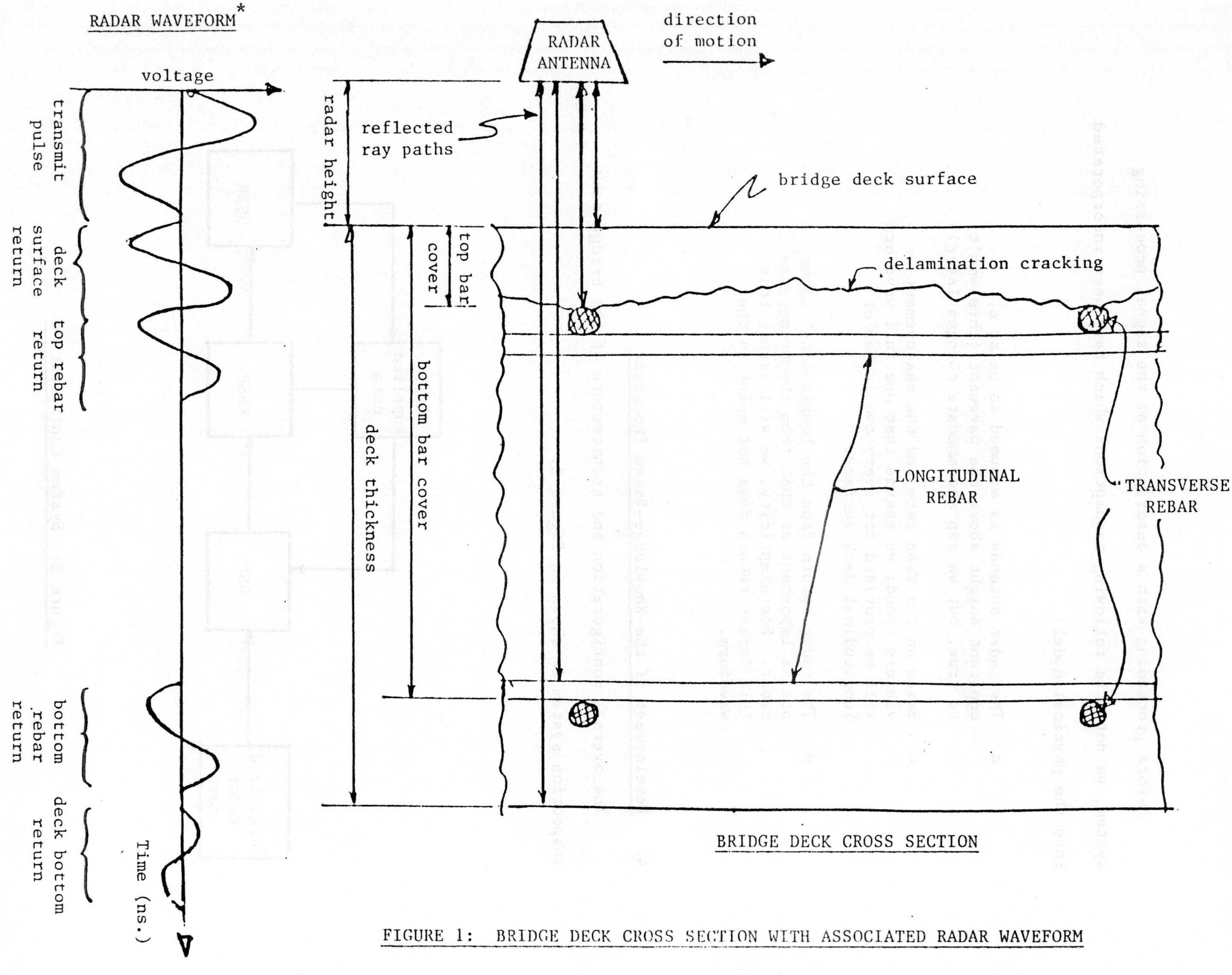

FIGURE 1: BRIDGE DECK CROSS SECTION WITH ASSOCIATED RADAR WAVEFORM

*Returns from longitudinal rebar have been eliminated for clarity.

Before proceeding with a description of the signal processing system, we note the following assumptions which have been incorporated into the physical model:

- The radar antenna is assumed to be at a constant height above the pavement (this won't be true, but we can accommodate changes later).
- Based on the scan rate and the measurement vehicle speed, we assume that one full waveform will be provided for every two inches of longitudinal deck surface.
- The radar return from the longitudinal rebar is not as important as that from the transverse rebar. For simplicity, we will assume that this former return does not exist in the waveform.

4. Development of the Knowledge-Based Processor

The overall configuration and architecture of the bridge deck inspection system is shown in Figure 2.

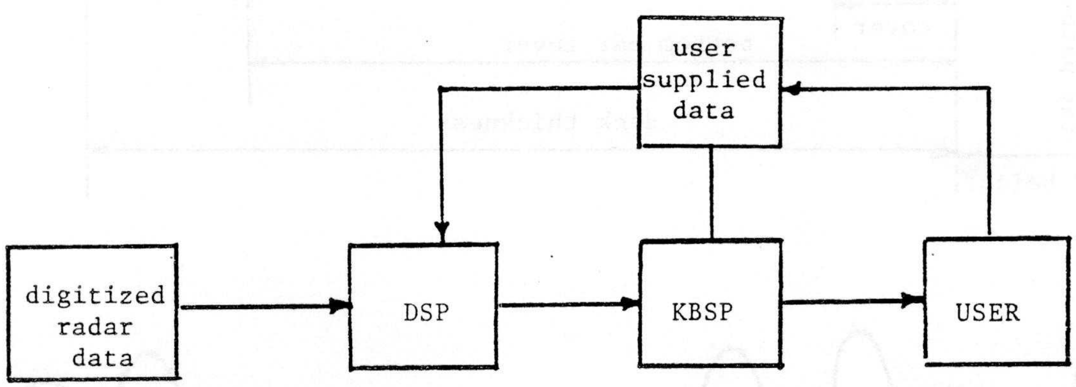

Figure 2: System Configuration

In this proposed configuration we assume the raw digitized radar data has been recorded and is being played back into the system. The user provides general information about the context of the measurement, initiates the analysis, and then lets the program be driven by the data. After the data is analyzed, the user may question the conclusions of the program and obtain explanations for these conclusions.

The two major elements of the analysis system are the digital signal processor (DSP) and the knowledge-based signal processor (KBSP). They are configured serially, with the DSP serving as a "front-end" to prepare the data for the KBSP (the limitations of this approach will be discussed later). The digital signal processor is assumed to carry out a number of tasks:

(1) It removes high frequency noise.

(2) It locates the first, second, and third negative peaks, and the fourth positive peak of the waveform. These peaks represent reflected pulse arrivals from the deck surface, the first rebar layer, the second rebar layer, and the bottom of the deck, respectively.

(3) It determines the arrival times and amplitudes of each of these peaks. The arrival time of the first negative peak is defined as zero, and subsequent arrival times are reported with reference to this zero. At this point, each waveform is represented by three pairs of numbers.

(4) It selects the waveforms produced when the radar antenna is directly over the rebar, by selecting the minima of the arrival times of all second negative peaks (i.e., when the radar is closest to the rebar). These will subsequently be identified by "ORB".

(5) It selects the waveforms produced when the radar antenna is midway between the rebar, by counting the number of scans taken between "ORB's", and taking the middle one. These will be identifed by "MRB". Waveforms

associated with all other scans are now eliminated from further processing.

(6) It multiplies each peak amplitude by $e^{\alpha x}$ where α is a default value for radar attenuation in concrete, and x is the expected position of the interface in the deck. This step normalizes for the expected attentuation in the radar signals, so that further processing can operate on numbers of similar magnitude.

The second, third, and fourth amplitudes and arrival times for contiguous ORB/MRB pairs, as determined by the steps above, are assumed to be passed on to the KBSP for further analysis. Each pair would thus define a 12 number signature for each "location."

For the purposes of this work, all of the above steps were assumed to be executable by conventional programming techniques. In the interest of time, we artificially produced the results of this process for each contiguous ORB/MRB pair and used these signatures as input to the KBSP for several locations.

The KBSP seeks to draw conclusions regarding the state of deterioration in the bridge deck at each location based on the signature produced at that location. The knowledge base includes knowledge of radar behavior, knowledge of deterioration phenomena in bridge decks, and knowledge about expected conditions in normal bridge decks. The knowledge representation is summarized in Table 1. Two typical rules and their applications are presented in Figure 3.

Note that certain pairs of rules associated with a given piece of knowledge (e.g. 17 and 22, 18 and 23) represent positive and negative findings. Other comments about the knowledge base will be discussed in Section 6, "Analysis."

TABLE 1

Summary of Knowledge Base

Domain	Knowledge	Rule No(s)
Radar	High attenuation is associated with high conductivity	16, 18, 21
	High conductivity is associated with low velocity	16
	Return time equals 2 times velocity divided by distance	19
Bridge Deterioration	Products of corrosion produce high attenuation	17, 22, 21
	High salt content in the concrete creates a high conductivity and a favorable environment for corrosion	27
	High salt content should produce high conductivity in the concrete covering the top rebar	21, 23
	Products of corrosion will infiltrate the concrete around the affected rebar	17, 22
	Products of corrosion and salts will infiltrate horizontal cracks connecting rebar	18, 23
	Thin concrete layer ("cover") over the top rebar creates a favorable environment for corrosion and cracking	25, 26
	Rebar corrosion leads to horizontal cracking	28-1
Bridge Engineering	Low top bar cover can result from misplacement of the bar, or from insufficient concrete placement over a properly located bar	19, 20
	Horizontal cracking represents the onset of deterioration	28-2
	A favorable environment for corrosion suggests that it may actually be occurring	28-3

```
;;; If we have calculated an actual-top-bar-cover which is 2 inches
;;; or more, and have concluded that conductivity is normal, and
;;; have evidence that there is no corrosion, and have evidence
;;; that there is no cracking, then there is probably no deterioration.

(defrule rule29
        (greaterq actual-top-bar-cover 2.0)
        (same conductivity normal)
        (thoughtnot corrosion yes)
        (thoughtnot cracking yes)

==>     (breakdown none 0.8))
```

```
;;; If both second and third mid-rebar reflections are
;;; attenuated, but arrive at about the expected time, then we
;;; probably have a crack. The crack does not delay the reflection,
;;; but does dissipate it, thus attenuating the signal which passes
;;; through and reflects off the bottom rebar and the deck base. The
;;; crack usually comes slightly below the top rebar so the reflection
;;; from the top rebar is not affected

(defrule rule23
        (lessq third-ampMRB 0.5)
        (lessq second-ampMRB 0.5)
        (between* second-time-differenceMRB -0.1 0.1)
        (between* third-time-differenceMRB -0.1 0.1)

==>     (cracking yes 0.5))
```

Figure 3: Typical Rules and Comments

The knowledge base is applied to relationships between various parts of a given signature, and to comparisons made between a given signature and the "expected" signature. The expected signature is computed from data input by the user, and from default parameters.

5. Discussions of Example

Seven examples, representing seven locations, were run using the mini-MYCIN Shell System and the knowledge base described above. Each example consisted of one signature containing 12 data points representing the various amplitudes and arrival times of selected peaks in the ORB and MRB waveforms. Each example was selected to highlight a different aspect of the knowledge base. The output for the example described as "location 2" is presented in Figure 4, and is discussed in further detail below.

The data for location 2 show high radar attenuation over the top rebar, normal attenuation below it, somewhat less attenuation for the mid-rebar bottom signal, and uniformly delayed arrival times. This signature was created to suggest the radar response due to products of corrosion.

Since the presence of corrosion and high conductivity were both concluded, we can see that the corrosion rule (22) and the high conductivity rule (21) must have fired, the latter because high attenuation is generally indicative of high conductivity. Rule 27 is fired, concluding that high conductivity creates an environment conducive to corrosion. Rule 28-1 is fired, concluding that the presence of corrosion suggests (Certainty Factor [CF] = .4) that pavement deterioration has begun. Rule 28-3 is also fired, concluding that if the environment is favorable for deterioration, then there is a possibility (CF.4) that it is actually occurring. These last two conclusions reinforce one another to conclude with CF.44 that pavement deterioration has begun.

6. Analysis of Results

The program performed as expected, and there were no major surprises. The knowledge base, however, could have been better organized and structured. For example, there are qualitatively three levels of findings: (1) environment favorable for deterioration; (2) corrosion in progress; and (3) deterioration (cracking has begun). Each level represents progressively increasing certainty regarding the

```
(run)

Assistant Concrete Bridge Deck Engineer

I will help interpret radar signals used to diagnose
deterioration of a concrete bridge deck  Please help
me get started by telling me what you already know about
the deck  Please enter times in nanoseconds, distances
in inches

Creating new context node  DECK-TEST-2
Enter value or list of values for BAR-SPACING
 from the allowed values  (NUMB)
 or nil if unknown
12 0

Enter value or list of values for BAR-DIAMETER
 from the allowed values  (NUMB)
 or nil if unknown
1 0

Enter value or list of values for TOP-BAR-COVER
 from the allowed values  (NUMB)
 or nil if unknown
2 0

Enter value or list of values for DECK-THICK
 from the allowed values  (NUMB)
 or nil if unknown
9 0

Enter value or list of values for RADAR-HEIGHT
 from the allowed values  (NUMB)
 or nil if unknown
6 0

Enter value or list of values for BOTTOM-BAR-COVER
 from the allowed values  (NUMB)
 or nil if unknown
6 0

Enter value or list of values for RADAR-VELOCITY
 from the allowed values  (NUMB)
 or nil if unknown
4 0

Any LOCATIONS for DECK-TEST-2 ? (y or n)  yes or no?
y

Creating new context node  LOCATION-2
Enter value or list of values for FIRST-TIMEORB
 from the allowed values  (NUMB)
 or nil if unknown
1 2

Enter value or list of values for SECOND-TIMEORB
 from the allowed values  (NUMB)
 or nil if unknown
3 2

Enter value or list of values for THIRD-TIMEORB
 from the allowed values  (NUMB)
 or nil if unknown
4 7

Enter value or list of values for FIRST-TIMEMRB
 from the allowed values  (NUMB)
 or nil if unknown
1 66

Enter value or list of values for SECOND-TIMEMRB
 from the allowed values  (NUMB)
 or nil if unknown
3 6

Enter value or list of values for THIRD-TIMEMRB
 from the allowed values  (NUMB)
 or nil if unknown
4 66

Enter value or list of values for FIRST-AMPORB
 from the allowed values  (NUMB)
 or nil if unknown
0 3

Enter value or list of values for SECOND-AMPORB
 from the allowed values  (NUMB)
 or nil if unknown
0 3

Enter value or list of values for THIRD-AMPORB
 from the allowed values  (NUMB)
 or nil if unknown
0 3

Enter value or list of values for FIRST-AMPMRB
 from the allowed values  (NUMB)
 or nil if unknown
0 4

Enter value or list of values for SECOND-AMPMRB
 from the allowed values  (NUMB)
 or nil if unknown
0 4

Enter value or list of values for THIRD-AMPMRB
 from the allowed values  (NUMB)
 or nil if unknown
0 4

Any more LOCATIONS for DECK-TEST-2 ? (y or n)  yes or no?
n
Based on the reflection arrival times and amplitudes you have
supplied my diagnosis is

Deterioration of LOCATION-2 is CONDUCIVE with certainty 0 68
Deterioration of LOCATION-2 is STARTED with certainty 0 44128
T

(case-tree)
 [1] DECK-TEST-2
        BAR-SPACING  12 0  CF  1 0  MB  1 0
        BAR-DIAMETER  1 0  CF  1 0  MB  1 0
        TOP-BAR-COVER  2 0  CF  1 0  MB  1 0
        DECK-THICK  9 0  CF  1 0  MB  1 0
        RADAR-HEIGHT  6 0  CF  1 0  MB  1 0
        BOTTOM-BAR-COVER  6 0  CF  1 0  MB  1 0
        RADAR-VELOCITY  4 0  CF  1 0  MB  1 0
        FIRST-TIME-EXPECTEDORB  1 0  CF  1 0  MB  1 0
        SECOND-TIME-EXPECTEDORB  3 0  CF  1 0  MB  1 0
        THIRD-TIME-EXPECTEDORB  4 6  CF  1 0  MB  1 0
        FIRST-TIME-EXPECTEDMRB  1 66000006  CF  1 0  MB  1 0
        SECOND-TIME-EXPECTEDMRB  3 4957427  CF  1 0  MB  1 0
        ANG1  0 6350113  CF  1 0  MB  1 0
        ANG2  0 4636478  CF  1 0  MB  1 0
 [2] LOCATION-2
        FIRST-TIMEORB  1 2  CF  1 0  MB  1 0
        SECOND-TIMEORB  3 2  CF  1 0  MB  1 0
        THIRD-TIMEORB  4 7  CF  1 0  MB  1 0
        FIRST-TIMEMRB  1 66  CF  1 0  MB  1 0
        SECOND-TIMEMRB  3 6  CF  1 0  MB  1 0
        THIRD-TIMEMRB  4 66  CF  1 0  MB  1 0
        FIRST-AMPORB  0 3  CF  1 0  MB  1 0
        SECOND-AMPORB  0 3  CF  1 0  MB  1 0
        THIRD-AMPORB  0 3  CF  1 0  MB  1 0
        FIRST-AMPMRB  0 4  CF  1 0  MB  1 0
        SECOND-AMPMRB  0 4  CF  1 0  MB  1 0
        THIRD-AMPMRB  0 4  CF  1 0  MB  1 0
        FIRST-TIME-DIFFERENCEORB  0 20000003  CF  1 0  MB  1 0
        SECOND-TIME-DIFFERENCEORB  0 104257256  CF  1 0  MB  1 0
        AMP RATIOMRB  1 33333333  CF  1 0  MB  1 0
        CONDUCTIVITY  HIGH  CF  0 7  MB  0 7
        CORROSION  YES  CF  0 7  MB  0 7
        CRACKING  YES  CF  -0 6  MB  0 5
        BREAKDOWN  CONDUCIVE  CF  0 68  MB  0 68
        BREAKDOWN  STARTED  CF  0 44128  MB  0 44128
```

FIGURE 4: PRINTOUT FOR LOCATION 2

existence of deterioration. It would have been helpful to organize the rules around these three levels, in order to clarify the selection and manipulation of certainty favors. (E.g., Rules 28-3 and 28-1 are inconsistent, since they reach the same conclusion with the same CF coming from different levels of findings.) Also, some of the rules are not representations of single pieces of knowledge. As seen in Table 1, some of the rules represent implicit combinations of radar knowledge and deterioration knowledge. From an explanatory point of view, it would be better to keep these pieces of knowledge separate. This requires greater care in creating the rules. (Note: the explanatory features have not yet been implemented.)

Finally, the rules were created to represent individual deterioration-related conditions, without regard to the impact of combined conditions on the validity of the rule. As a result, an example at another location, which was intended to combine all conditions, concluded no cracking, since the cracking rule was negated by the conditions of low concrete cover. Future efforts should seek to make each rule representing a condition independent of other conditions present.

7. Discussion

There are important differences between the MYCIN domain and the domain we are considering. In medicine, the presence of an organism from any culture taken at any location implies a disease in the whole body. In structures, the presence of deterioration at any location means only that, and the general condition of the structure must be built up from the collective locations such individual evidences. In medicine, an organism is an organism. It's there or it isn't. In structures and materials, deterioration must be distinguished from normal variations of in-situ conditions.

In-situ field measurements never rely on absolute reference values for parameters like radar velocity and attenuation. Rather, some type of calibration is made in the field, or inferred from the field data. In addition, data from "as-built" drawings is often inaccurate due to variability in construction procedures. These corrections usually involve reasoning about spatial patterns. That is, if a certain combination of signatures show up in a certain way over a certain number of locations, then we can conclude (based on our knowledge of bridge decks, and this one in particular) that the radar velocity is really x, the attenuation coefficient is really y, and the rebar geometry is z. Carrying out such analysis involves comparing data from location to location, an activity precluded in the MYCIN context tree structure. Two other types of desirable spatial reasoning are building confidence in a deterioraton conclusion using supporting evidence from adjacent locations, and distinguishing deterioration from normal variations based on spatial distribution patterns.

Mini-MYCIN's style of data entry was inconvenient. Our application requires that sensory data be directly transmitted to the KBSP from the DSP. Mini-MYCIN and many other expert system shells assume that the user is the sole supplier of data.

A final comment relates to the serial structure of the DSP-KBSP combination. In reality, people who analyze signal data compute and reason interactively. The data is processed one way, examined, and if it doesn't make sense it is processed another way, etc. Likewise, the DSP-KBSP components of the proposed system should interact. For example, the peak detection algorithm usually has a threshold value which distinguishes "significant" peaks from insignificant maxima and minima. One possible interaction would be an inconclusive response from the KBSP suggesting a change in this threshold value. Other parameters in the DSP could also be adjusted and alternative algorithms could be invoked based on conclusions from the KBSP.

The above conclusion regarding the interaction of computation and reasoning characterizes many areas of engineering. In these applications, the knowledge-based system may be more appropriately regarded as a module of a larger system, which invokes the KB-system at appropriate points in its analysis. Shell systems with this modular capability would be of great value in future engineering applications.

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