A real-time expert control system

Zi-Xing Cai*, Yao-Nang Wang† & Jing-Feng Cai*

*Department of Automatic Control Engineering, Central South University of Technology,
Changsha, 410083, People's Republic of China
†Department of Electrical Engineering, Hunan University, Changsha, 410082, People's Republic of China

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A new developed and designed real-time expert intelligent control system (REICS) for industrial process control has been introduced. The global architectures of the hardware and software of the system have been proposed. A multi-level method of knowledge representation based on the combination of frame, production rules and real-time procedures has been discussed, and used to represent the control knowledge and algorithms of the control system. Meanwhile, the reasoning mechanism, control strategy and its flow chart have been presented. The simulation and the practical application of an industrial rotary kiln furnace for the proposed tool and method have been described.

Key words: real-time control, expert system, intelligent control, temperature control.

1 INTRODUCTION

Real-time expert control is a combination of artificial intelligence, expert systems, fuzzy sets, and control theory, and is a newly developing direction with promising application for intelligent control.1-4 This method can solve the control problems of large-scale and complex systems with time variance, nonlinearity, and multidisturbance in the real-time control process. This developed control system possesses the versatility and capability for processing control knowledge with uncertainty. REICS-SHELL, a general development tool for real-time expert intelligent control systems (REICS), is introduced in this paper.5

2 STRUCTURE

The global structure of the hardware and software of the REICS are shown in Figs 1 and 2 respectively. For the system hardware the microprocessor IBM PC-386 is used for decisions and computation in the high-level expert system; the A/D and D/A converters as well as the interfaces are used in the low level circuits. The software of REICS consists of the modules for the dynamic database, real-time inference engine, information preprocessor, interpreter, set of control algorithms, data communication interface, and human-machine interface, etc. The inference engine and knowledge representation are implemented using the programming language Turbo-prolog, and the programming language C is used to compute the set of control algorithms and data communication.

In the global design of REICS, we have proposed a generalized production system based on a frame, production rules, and real-time procedure; this generalized production system is used to represent control knowledge and algorithms for the control system. In the highest control level, the organization level, the reasoning knowledge is represented by the frame, and the imprecise reasoning and the choice of control strategy are carried out by fuzzy approximate reasoning. In the coordination level, the coordination control knowledge is represented by the generalized production rules; the choice of control algorithms, parameter self-tuning rules, and parameter evaluation are performed by backward reasoning and refined uncertainty reasoning. In the real-time control level, the forward real-time reasoning is done according to the reasoning and decision-making results of the above two higher control levels and the sampled real-time data (facts); as a result the real-time control input of the controlled object at any time is given.

3 KNOWLEDGE REPRESENTATION

The key to expert intelligent control is to make intelligent decision through problem solving. Therefore it is important for implementing intelligent control to...
build a good model of knowledge representation for problem solving. Because the knowledge of object characteristics and parameter rules in the control domain is very complex, the different control objects may use different control knowledge. As mentioned above, a generalized production system tool, REICS-SHELL, was developed and used to represent the multilevel knowledge.

3.1 Production rule

A generalized production rule has the form:

\[
\text{IF} \{\text{frame}(X_1 \text{ is } a_1) \land (X_2 \text{ is } a_2) \land \cdots \land (X_n \text{ is } a_n) \rightarrow (Y_1 \text{ is } B_1)\}
\]

THEN \{IF(rule(K_1 \land K_2 \land \cdots \land K_n)P_i CF(P_i, K_i))

THEN \langle \text{process}(S_1(t_1) \land S_2(t_2) \land \cdots \land S_n(t_n)) \rightarrow U_i(t_i)\rangle\}

(1)

where: \(Y_i \in \text{control strategies}\), and includes ES-PID, ES-Fuzzy, ES-Predict, and ES-Adaptive, which stand for the expert intelligent PID control, expert fuzzy control, expert intelligent predictive control, and expert intelligent adaptive control, respectively; \(X_i \in \text{characteristic knowledge of control object}\); \(B_i, a_i\) are variable values of the fuzzy set; \(K_i \in \text{preconditions of rules including facts, parameters, and real-time sample data, etc.}\); \(P_i \in \text{the combination of control algorithms, evaluated algorithms, control rules, and parameter}\).
regulation rules; \( CF(P_i, K_i) \) is the imprecise reasoning function; \( S_i(t_i) \) is the control process at a given time; \( U_i(t_i) \) is the output of the control system REICS at a given time.

### 3.2 Frame rule

The frame rule of the knowledge representation in the organization level has the form:

\[
((\text{plant})(\text{mathematical model } X_1)(\text{character}))
\]

\[
((\text{nonlinearity } X_2)(\text{character}))
\]

\[
((\text{time-delaying } X_3)(\text{character}))
\]

\[
((\text{time-varying } X_4)(\text{character}))
\]

\[
((\text{parameter variation } X_5)(\text{character}))
\]

\[
((\text{inertia } X_6)(\text{character}))
\]

\[
((\text{disturbance } X_7)(\text{character}))
\]

\[
((\text{dynamic response } X_8)(\text{character}))
\]

\[
\ldots
\]

\[
((\text{control strategies})(\text{ES-PID})
\]

\[
\text{ES-Fuzzy}
\]

\[
\text{ES-Predict}
\]

\[
\text{ES-Adaptive})
\]

where \( \langle \text{plant} \rangle \) stands for the controlled object. The structure of the knowledge base in the organization level corresponds to the following form:

\[
\text{frame}([X_1(A_1), \ldots, X_n(A_n)], Y(B_i)); \text{ predicate (3)}
\]

where \( A_i, B_i \in \{\text{BO, MO, SO, ZO, DO}\} \), i.e. \{big, medium, small, zero, undefined\} and are variable values of fuzzy statement. This frame rule can be rewritten as

\[
\text{frame}([X_1(\text{ZO}), X_2(\text{MO}), X_3(\text{BO}), X_4(\_), X_5(\text{BO}), \ldots], Y(\text{ES-PID}), B_i(\text{BO})); \text{ predicate (4)}
\]

### 3.3 Refined rule

The refined rule for the coordination level has the form:

\[
\text{rule IF } (A, C(A)) \text{ THEN } (B, C(B))CF(B, A)
\]

\[
A \in \{K_1 \land \ldots \land K_n\}
\]

\[
B \in \{P_1, P_2, \ldots, P_m\}
\]

\[
CF(B, A) : A \rightarrow B \in [-1, 1]
\]

\[
C(\_): U \rightarrow [0, 1]
\]

where \( A \) is antecedent of the rule and presents facts, evidence, hypotheses, the real-time database and objectives; \( B \) is consequent of the rule and comprises starting a control or evaluation algorithm or adding a new element to the knowledge base; \( C(\_) \) represents the uncertainty level of evidence; \( CF(B, A) \) describes the knowledge uncertainty as the confidence (certainty factor) value of a rule, i.e. the confidence with which the facts in antecedent \( A \) support the conclusion in consequent \( B \). \( CF(B, A) \in [-1, 1] \); if \( CF(B, A) = -1 \), then \( A \) is false and the operation in \( B \) is negative absolutely; if \( CF(B, A) = 1 \), then \( A \) is true and the operation in \( B \) is positive absolutely; if \( CF(B, A) = 0 \), then \( B \) is independent of \( A \).

### 4 INFERENCE MECHANISM

The core of REICS is the inference engine that can select related knowledge according to a reasoning strategy and make inferences for control algorithms, facts, evidences provided by control experts, and data acquired from real-time sampling. As a result the corresponding decisions for intelligent control can be made and used to guide the control action. The inference mechanism includes the inference method and the control strategy; it possesses the capability (1) to process imprecise knowledge, (2) to do real-time reasoning rapidly, (3) of high reliability of control in the on-line operation, and (4) of wide versatility.

The reasoning consists of three levels; the global flow diagram of the control strategy is shown in Fig. 3. We discuss the reasoning mechanism for the three levels in detail as follows.

#### 4.1 Reasoning in organization control level

In the highest control level, the organization level, the approximate reasoning of fuzzy sets is employed to handle the fuzzy knowledge in frames, and the reduction heuristic matching search technique of AI is used to search for the goal. The algorithm for handling the fuzzy knowledge is explained as follows.

The frame searching rules for matching are:

\[
\text{frame}((X_1 \text{ is } a_1 \land X_2 \text{ is } a_2 \land \ldots \land X_n \text{ is } a_n)
\]

\[
\rightarrow Y_1 \text{ is } B_1
\]

\[
\text{frame}((X_1 \text{ is } a_{21} \land X_2 \text{ is } a_{22} \land \ldots \land X_n \text{ is } a_{2n})
\]

\[
\rightarrow Y_1 \text{ is } B_2
\]

\[
\ldots
\]

\[
\text{frame}((X_1 \text{ is } a_{n1} \land X_2 \text{ is } a_{n2} \land \ldots \land X_n \text{ is } a_{nn})
\]

\[
\rightarrow Y_1 \text{ is } B_n
\]

where \( a_{ij} \in \{\text{ZO, SO, MO, BO, DO}\} \).

#### 4.2 Reasoning in the coordination control level

In the medium level, the coordination control level, the reasoning process is as follows: (1) access the conclusion from the organization level in the dynamic database and
use it as hypothesized goal of the coordination level; (2) search for rules that can reach the goal, then draw a set of conclusions; (3) find a premise of the optimal rule by using a refined algorithm with imprecise reasoning, and use it as the new supposed goal for further reasoning until a solution of the problem is found. During operation, the user can exhibit the record of every step in the reasoning process by using the predicate why. After a conclusion is drawn, the user can inquire how the conclusion is drawn by means of the predicate how.

The refined algorithm with imprecise reasoning provides the value of uncertainty about the conclusion, i.e. the uncertainty of the dynamic strength and knowledge, and is derived using the uncertainty about the evidence.

4.3 Reasoning in the real-time control level

During real-time operation in REICS, forward reasoning is used, i.e. reasoning from initial data to control goal. First, based on reasoning in the two higher control levels, the current information $E = \{e, \dot{e}, Y, U, R, K_p, \ldots\}$ provided by the information preprocessor and the dynamic database is used as the precondition. Then the control rule that matches with this precondition in the dynamic database is sought. If the match is successful, then the state goal is found and a series of control actions about the conclusion of the rule is carried out, e.g. computation of the current control parameters and control value, D/A and A/D conversion, data sampling, control action transfer, and information reception etc. If the match is not successful, then the search for a matched rule should be continued.

5 SIMULATION AND APPLICATION

In order to examine the range and effect of application after design and implementation, we have done an experimental study of the system on the IBM PC-386
A real-time expert control system

Fig. 4. Output of the plant for Example 1.

microprocessor by inserting a control interface with multiple functions.

Four kinds of intelligent control algorithms have been included in the REICS: ES-PID, ES-Fuzzy, ES-Predict, and ES-Adaptive, all installed into control algorithm base. Meanwhile some control rules should be input.

5.1 Examples of simulation

Example 1

The controlled plant is a nonlinear system with a stochastic disturbance acting on it. The mathematical model of the plant is in the form:

\[ y(t) = \frac{y(t - 1)e^{-y(t-1)} + u(t - 1)}{1 + u(t - 1)e^{-y(t-1)}} + \omega(t) \]

where \( \omega(t) \) is a white noise with standard variance 0.15. The step response of the plant is illustrated in Fig. 4.

Example 2

The plant is a nonlinear system with a large time delay, i.e.

\[ y(t - 1)y(t - 2)u(t - 3)y(t - 4)u(t - 4) \]

\[ y(t) = \frac{-y(t - 1)y(t - 2)y(t - 3)u(t - 4) + u(t - 5)}{1 + y^2(t - 3) + y^2(t - 4)} \]

where the time delay \( d = 4 \). Figure 5 illustrates the step response curves of the plant under REICS control.

In Figs 4 and 5, three different controls were compared through simulation, i.e. (1) conventional PID control, (2) fuzzy control, and (3) REICS control.

A comparison of robustness among PID, fuzzy control, and REICS was simulated for two cases: (a) as the object’s parameter was changed, (b) as an exotic disturbance was induced. The simulation results show that the REICS has a better adaptivity to a parameter’s change and a better capability of antidisturbance than those of PID and fuzzy control. From the experiments it can be drawn that REICS possesses a stronger robustness than PID and fuzzy control systems do.

5.2 Application for temperature control of a rotary kiln furnace

As an application of REICS, the proposed control scheme was applied to the temperature control of an industrial rotary kiln. The temperature control system can be divided into five main components: the rotary kiln furnace, the temperature sensor module, the programmable input output interface board, the microcomputer, and the actuator. The interface circuit board consists of an analogue-digital (A/D) converter, a digital-analogue (D/A) convertor, and a programmable peripheral interface device. An external clock is designed to operate the A/D and D/A convertors. The microcomputer used in the system is the IBM PC-386 with

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an Intel 80386 32-bit CPU with a 40 MHz clock speed. The REICS control programs were written using Turbo-C to provide the control input to the actuator through the D/A and also to measure the output temperature.

In the industrial experiment, the sampling time was 30 s, and the set points were 500°C and 1000°C respectively. Figures 6 and 7 illustrate the temperature response of the kiln furnace. When the system knows a little about the controlled process, the REICS can provide the initial control by imitating the actions of human expert operators.

The REICS controlled industrial rotary kiln furnace has been operated successfully in Zhengzhou Aluminum Plant, China, since August 1994. If the initial weight values and the expert controlled parameters, such as control error and threshold of error ratio, are selected properly, then the control system can be implemented with the following performance: (1) very small or almost no overshoot; (2) less regulating time; (3) no oscillation; (4) high control accuracy of temperature (within ±2°C). Industrial operation has shown that the REICS is effective for real-time control for systems with large delays and strong nonlinearity.

6 CONCLUDING REMARKS

REICS-SHELL is a development tool for real-time control systems implemented in an IBM PC-386 microprocessor system. The results of research both in simulation and applications have shown that REICS possesses many advantages, such as flexible control strategy, easy knowledge acquisition, the ability to process control knowledge with uncertainty, good real-time control capability, adaptivity, and versatility. When using this REICS-SHELL tool, one simply adds control rules and revises rules, facts, and control algorithm parameters in the knowledge base. Therefore this tool is available for industrial process control systems with uncertainty and imprecise mathematical models.

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