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APPLICATION OF FUZZY LOGIC FAULT ISOLATION METHODS FOR ACTUATOR DIAGNOSIS

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Abstract: Four fuzzy logic fault isolation methods suitable for implementation in smart final control elements are proposed. The methods are suited for real time diagnostics applications considering computing power limitations typical for applications in intrinsically safe zones. The comparison of isolability features of presented algorithms is given in examples. *Copyright © 2002 IFAC.*

Keywords: actuators, positioning systems, fuzzy logic, fault detection, fault isolation, information systems.

1. INTRODUCTION

Control tasks of technological processes may be generally defined in the terms of acting on the energy and mass flows. Actuators (final control elements) are applied for real-time acting on this flows. Faults or malfunctions of final control elements (e.g. control valves, servo-motors, positioners) are appearing relatively often in the industrial practice. The actuators are installed mainly in harsh environment: high temperature, high pressures, low or high humidity, dusty pollutants, chemical solvents, aggressive media, vibrations, etc. This has the crucial influence on the final control element predicted lifetime. The malfunction or failures are causing long-term process disturbs or even sometimes forces the installation shut down. Moreover, final control elements faults may vary final product quality may cause also a reasonable economic losses. For fault prevention or prediction, the on-line diagnostics of final control elements may be applied. Continuously or periodically performed diagnosis of actuators cuts the maintenance costs. The introduction of remote on-line diagnostic of actuators may bring down the periodical inspection costs by factor 50-70%. In such cases the inspections and repairing of the actuators are undertaken only if necessary. In the recent 20 years there were developed a numerous of fault detection and isolation methods. The problems of actuator diagnosing were also considered. For fault detection and isolation many different approaches were used, for example:

- parity equation (Massoumia and Van der Velde, 1988; Mediavilla, *et al*. 1997)
- unknown input observer (Phatak and Wiswanadham, 1988)
- extended Kalman filter (Oehler, *et al*. 1997)
- signal analysis (Deibert, 1994)
- fuzzy logic (Kościelny and Bartyś, 1997; Kościelny 1999)
- b-spline (Benkhedda and Patton 1997).

The analysis of possible faults of assembly: control valve, pneumatic servo-motor was studied by Koj, (1998). There were also developed intelligent

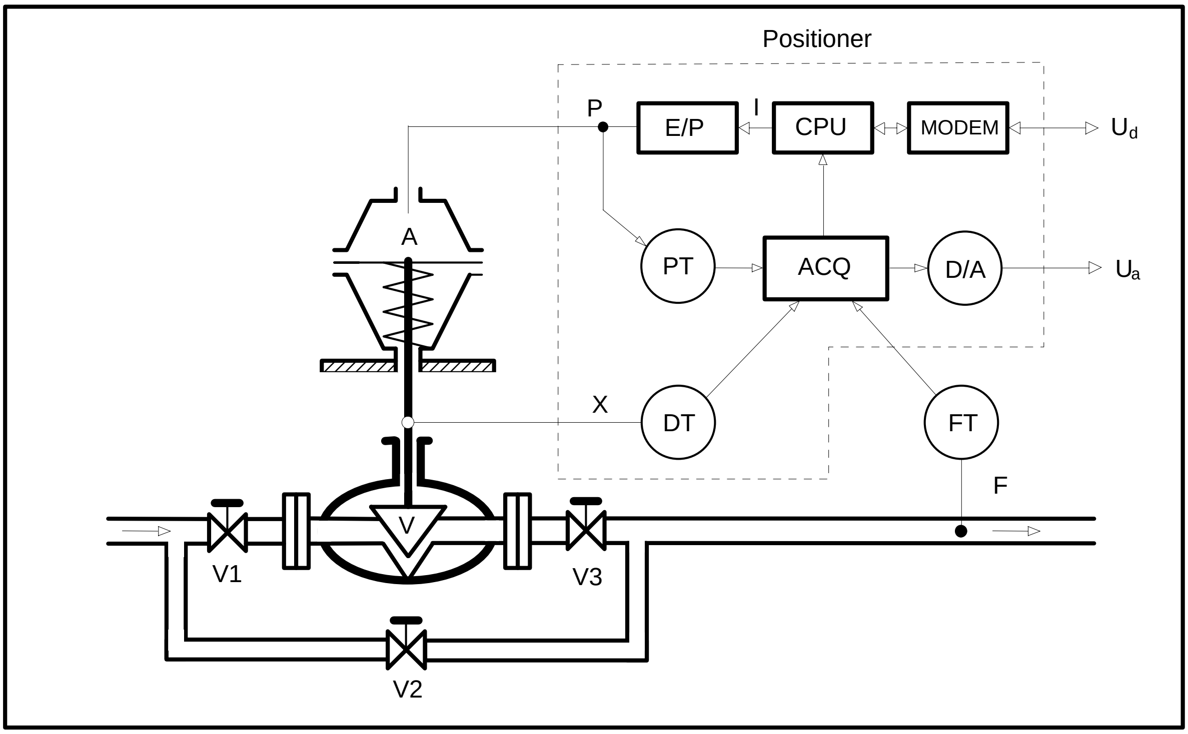

Fig.1. Diagram of the control valve-pneumatic servo-motor positioner assembly. Notations:

A	- pneumatic servo-motor
V	- control valve,
V1,V2,V3	- bypass valves
CPU	- positioner central processing unit
ACQ	- data acquisition unit,
MODEM	- system for digital communication
D/A	- digital-to-analogue converter
U_d	- digital communication link
U_a	- analogue communication link (option)
E/P	- electro-pneumatic transducer
DT	- displacement transducer
PT	- pressure transducer
FT	- volume flow rate transducer
I	- control current of E/P transducer
P	- output pressure of the E/P transducer
F	- volume flow rate signal

positioners supporting auto diagnostic functions (Bayart and Staroswiecki, 1991; Isermann and Raab,1993; Kościelny and Bartyś, 1997; Yang and Clarke, 1997). The decomposition of the diagnostic tasks in the complex systems and the concept of intelligent actuators providing diagnostic features were also presented in papers (Bouras and Staroswiecki, 1998; Kościelny and Bartyś, 1997).

2. THE SET OF FAULTS OF THE ASSEMBLY: CONTROL VALVE, SERVO-MOTOR, POSITIONER

Assembly consisting of: control valve, diaphragm-spring pneumatic servo motor and positioner belongs to the most popular final control elements applied in the industrial practice. Fig. 1. shows the diagram of assembly. There are taken into account following realistic assumptions that for diagnostics are available following signals: U - positioner set point signal, I - control current of electro-pneumatic transducer, P - pressure controlling pneumatic servo-motor, X – servo-motor piston rod displacement, F - media volume flow rate.

Faults may appear in: control valve, servo-motor, electro-pneumatic transducer, XT transducer, PT transducer and microprocessor control unit. The internal faults of microprocessor control unit are detected autonomously by auto diagnostic procedures. This is the reason that control unit faults are not further considered.

Let us assume that the set of possible primary faults of the final control element is known (Koj, 1998; Kościelny and Bartyś, 2000). The total of 19 faults $\{f_1 .. f_{19}\}$ are distinguished. The faults are classified into four following groups:

- Control valve faults $\{f_1 .. f_7\}$
- Pneumatic servomotor faults $\{f_8 .. f_{11}\}$
- Positioner faults $\{f_{12} .. f_{14}\}$
- General faults/external faults $\{f_{15} .. f_{19}\}$

3. PROBLEM STATEMENT

Let us assume, that the reference set of relations faults-symptoms are defined in the form of binary or three-valued matrices and minimal set of diagnostic tests (Kościelny and Bartyś, 2000) is known.

Binary or three-valued symptom evaluation has an disadvantage when considering symptoms uncertainty. This may be solved for example by applying given below fuzzy logic based approaches.

Let *j-th* symptom s_{kj} of *k-th* fault have a form of binary pair *<0, 1>* or FIS triplet *<-1, 0, 1>* (Kościelny, 1999; Kościelny and Bartyś, 2000) based on rough sets theory (Pawlak, 1991).

FIS - Fault Isolation System is defined as:

$$FIS = < F, S, V, R_{FS} > \tag{1}$$

where: *F*- set of faults (objects), *S* - set of diagnostic signals (attributes), *V* - set of all diagnostic signal values, while

$$V = \bigcup_{s_j \in S} V_j \tag{2}$$

R_{FS} - function attributing to each of the pairs fault-diagnostic signal <f, s>, value or values:

$$R_{FS}: F \times S \rightarrow r(V) \tag{3}$$

$$r_{FS}(f_k, s_j) = V_{kj} \subset V_j$$

The FIS defines pattern values of diagnostic signals for particular faults. If the diagnostic signal (residuum) is normalised in the range [0, 1] then the symptom value can be interpreted as a value of a fuzzy set. This set will be further called as a fuzzy symptom set. If normalised crisp residuals r_{nj} ($j=\{1..J\}$; *J* - diagnostic test count) are available then the fuzzy diagnostic signals (fuzzy symptoms) are obtained by fuzzyfication of r_{nj} values. In that case symptom value can be interpreted as a value of membership function of fuzzy symptom.

Let us define *j-th* fuzzy diagnostic signal as the fuzzy variable <Fs_j> Let fuzzy diagnostic signal will have three symmetrical terms: <***-1***>, <***0***>, <+***1***> as shown on Fig. 2. Fuzzy diagnostic terms <***-1***>, <***0***>, <+***1***> are analogue to fuzzy diagnostic test results with constant threshold (Mediavilla M., *et al.*, 1997) where <***-1***> and <+***1***> terms are denoting negative test results, why <***0***> term denotes positive result (fuzzy fault free state). Fuzzy diagnostic tests results can be therefore defined as vector of *J* membership function pairs <μ_{0nj}, μ_{-1nj}, μ_{+1nj}> related to *J* fuzzy diagnostic tests with normalised thresholds $\pm T_{nj}$

$$S_f = \left\{ < \mu_{0nj},\ \mu_{-1nj},\ \mu_{+1nj} > j = 1,2,...,J \right\} \tag{4}$$

The fault detection is principally based on the tests of conformity of fault reference signature and current (real time in the case of on-line diagnostics) set of symptoms. It means that fault (faults) are detected only and only when the current diagnostic signals *S*

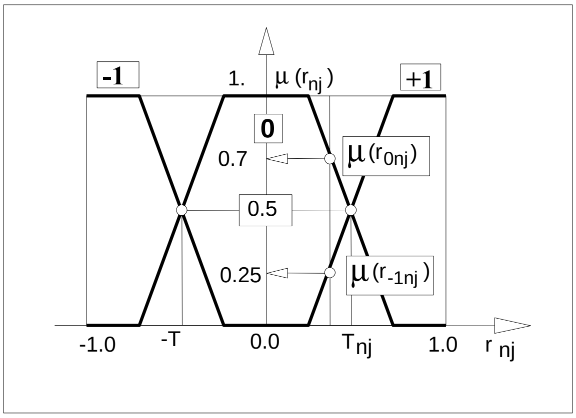

Fig. 2. Example of fuzzy symptom of j-th normalised fault residual r_{nj}. Notations: T_{nj} – crisp threshold (see table 2), ***-1, 1*** – negative fuzzy diagnostic test results (fuzzy faulty states), ***0*** – positive fuzzy diagnostic test result (fuzzy fault free state).

vector is equal to *k-th* fault reference signature S_{rk} . This can be rewritten in the form:

$$\textbf{\textit{if}}\ ((s_1 = s_{r1,k}) \cap (s_2 = s_{r2,k}) \cap ..(s_J = s_{rJ,k}))\ \textbf{\textit{then}}\ f_k \tag{5}$$

where: s_j – *j-th* current diagnostic signal
s_{rjk} – *j-th* reference symptom of *k-th* fault

3.1 Minimum approach

Term (5) one can interpret as a fuzzy rule of a fuzzy system, if s_j crisp diagnostic signals will be replaced by its fuzzy analogues. In that case the conclusion from conditional relation (5) is equal to firing level τ_k of the rule premise in the range of [0,1]. If the firing level τ_k is more close to 1 then conclusion (fault f_k) is more certain.

For the simplicity, of the presented below fault isolation algorithms and conformity to FIS notation let us assume that reference values s_{rjk} are tri-valued *< 0, -1, +1>*. The relation (5) can be therefore modified to the form of conformity conjunction:

$$if\ \ (\tau_{1k}\ \cap\ \tau_{2k}\ \cap .. \cap\ \tau_{Jk}\ \cap)\ then\ \ f_k \tag{6}$$

where for FIS:

$$\tau_{jk} = \max\left(\tau^0{}_{jk},\ \tau^{-1}{}_{jk},\ \tau^{+1}{}_{jk}\ \right) \tag{7}$$

$$\begin{cases} \tau^0{}_{jk} = \ \mu_{0j} \quad for\ s_{rjk} = \ \ 0 \quad otherwise\ \tau^0{}_{jk} = \ 0 \\ \tau^{-1}{}_{jk} = \ \mu_{-1j}\ \ for\ s_{rjk} = -1 \quad otherwise\ \tau^{-1}{}_{jk} = \ 0 \\ \tau^{+1}{}_{jk} = \ \mu_{+1j}\ \ for\ s_{rjk} = +1 \quad otherwise\ \tau^{+1}{}_{jk} = \ 0 \end{cases} \tag{8}$$

and for binary valued reference signatures:

$$\tau_{jk} = \max\left(\ \tau^0{}_{jk},\ \ \tau^1{}_{jk}\right) \tag{9}$$

$$\begin{cases} \tau^0{}_{jk} = \mu_{0j} \quad for\ s_{rjk} = 0 \quad otherwise\ \tau^0{}_{jk} = 0 \\ \tau^1{}_{jk} = \bigcup\{\mu_{-1j},\ \mu_{+1j}\}\ for\ s_{rjk} = 1\ otherwise\ \tau^1{}_{jk} = 0 \end{cases} \tag{10}$$

When applying Mamdani's inference scheme the fuzzy inference from (6) is equal to intersection of τ_{jk} sets:

$$\tau_k = \bigcap_{\forall j \in \{1,J\}} \tau_{jk} \tag{11}$$

Diagnosis will be defined as a set of pairs:

$$DGN_f = \left\{ < \tau_k\ ,\ f_k\ > \right\}\ \forall k \in \left\{ 1..K \right\} \tag{12}$$

Diagnosis can be also interpreted as the discrete fuzzy set τ_k defined in universe of discourse *{F:f_k∈F}*. Therefore exists simple graphical interpretation of diagnosis (12) very useful in practical applications. Moreover the τ_k value from (12) is extremely easy and fast to calculate.

3.2 Multiplicative approach

Main disadvantage of minimum approach is that diagnosis results are equal if the minimum values of fuzzy conformity factors are the same even if the other factors τ_{jk} are substantially different. This leads to the conclusion that results of minimum approach are sensitive to measurement noise. Let us consider the following multiplication formula that improves diagnosis noise immunity

$$\tau_k = \frac{\prod_{\forall j \in \{1,J\}} \tau_{jk}}{\sum_{\forall k \in \{1,K\}} \prod_{\forall j \in \{1,J\}} \tau_{jk}} \tag{13}$$

Fuzzy symptom evaluation is still considered however one can see that following simplified fuzzy inference scheme is applied:

$$\prod_{\forall j \in \{1,J\}} \tau_{jk} \approx \bigcup_{\forall j \in \{1,J\}} \tau_{jk} \quad : \quad \tau_{jk} \in [0,1] \tag{14}$$

The expression in denominator of (13) is only normalising the τ_k value into standard [0, 1] range. The Π and Σ operators, have wider meaning comparing to ∩ operator in expression (11). By multiplication of τ_{jk} values the effect similar to fuzzy concentration operator is achieved. This brings an effect of *"gaining"* the most certain diagnosis (this with τ_k value close to 1) and *"damping"* diagnoses with τ_k close to 0. This effect could be evaluated as positive from the application point of view, however when applying the multiplication method more computational power expenses must be taken into account comparing to minimum approach. To solve this problem the following simplified form of equation (11) can be applied for real time applications.

$$\tau_k = \prod_{\forall j \in \{1,J\}} \tau_{jk} \tag{15}$$

3.3 Additive approach

Minimum and multiplication approaches are sensitive to particular case when one of conformity factors τ_{jk} is equal to zero. This does not guarantee sufficient immunity in noisy industrial environment. When introducing more robustness into fault isolation system this effect have to be overcome. From other side, on-line applicability forces relative simplicity of the approach. Fuzzy symptoms and fuzzy signature conformity measure may be assumed as normalised τ_k fuzzy set power.

$$\left|\tau_k\right|_n = \frac{1}{J}\sum_{j=1}^{J} \tau_{jk} \tag{16}$$

The absolute conformity of current symptoms and k-th fault signature is achieved when $|\tau_k|_n=1$. Because of integrating properties of Σ operator the diagnosis from (14) is less sensitive for measurement noise. Σ operator brings the effects comparable to fuzzy dilution operator, what *"flattened*" diagnosis.

3.4 Mixed approach

To combine the advantages of presented above approaches and minimise its disadvantages the mixed approach may be considered. Let us assume following diagnosis conformity factor:

$$\tau_k = \frac{\sum_{j=1}^{J} \tau_{jk}}{\sum_{k=1}^{K}\prod_{j=1}^{J} \tau_{jk}} \cdot \frac{1}{\bigcup_{k=1}^{K}\sum_{j=1}^{J} \tau_{jk}} \tag{13}$$

where: $1/\bigcup_{k=1}^{K}\sum_{j=1}^{J} \tau_{jk}$ scaling factor

Both, nominator and denominator have integration properties what ensure appropriate immunity against noise. The denominator joins a concentration action and dilution one. This actions seems to be slightly balancing each other.

3. EXAMPLES

Assume availability of FIS table, (see table 1) (Kościelny and Bartyś, 2000) for assembly consisting of: control valve, servomotor and positioner.

Example 1

Let the set of current fuzzy symptoms is as follows: *FS = {s_1={0, 1, 0}, s_2={0.4, 0.6, 0.0}, s_3={1, 0, 0}, s_4 = {0.1, 0.9, 0.0}, s_5={1, 0}, s_6={0.8, 0.2}}*

The τ_{jk} values (fuzzy symptom conformity table with references given in table 2, the diagnoses obtained from four fault isolation methods presented in the paper are shown in table 3. For comparability of the results the formula (15) is used for determining values of multiplicative method.

Table 1. Fault Isolation System reference for assembly: control valve- servomotor-positioner

FSS	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{18}	f_{19}
s_1	0	0	0	0	0	0	0	0	-1	-1	0	+1 -1	0	+1 -1	-1	0	0	0	0
s_2	+1 -1	-1	0	+1 -1	0	0	0	+1 -1	0	-1	+1	0	+1 -1	+1 -1	0	0	0	0	0
s_3	0	-1	+1	0	-1	+1	-1	0	0	0	0	0	+1 -1	0	0	+1	-1	+1	+1 -1
s_4	+1 -1	-1	0	+1 -1	0	0	0	+1 -1	-1	-1	+1	+1 -1	+1 -1	0	-1	0	0	0	0
s_5	1	0	0	0	0	0	0	0	0	0	0	0	0 1	0 1	0	0	0	0	0
s_6	0	0	1	0	0	1	0	0	0	0	0	0	0 1	0	0	0	0	0	0 1

Table 2. Fuzzy symptom conformity table and diagnosis for assembly: control valve- servomotor-positioner (example 1)

FSS	f1	f2	f3	f4	f5	f6	f7	f8	f9	f10	f11	f12	f13	f14	f15	f16	f17	f18	f19
s_1	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	0	0	0	0
s_2	0.6	0.6	0.4	0.6	0.4	0.4	0.4	0.6	0.4	0.6	0	0.4	0.6	0.6	0.4	0.4	0.4	0.4	0.4
s_3	1	0	0	1	0	0	0	1	1	1	1	1	0	1	1	0	0	0	0
s_4	0.9	0.9	0.1	0.9	0.1	0.1	0.1	0.9	0.9	0.9	0	0.9	0.9	0.1	0.9	0.1	0.1	0.1	0.1
s_5	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
s_6	0.8	0.8	0.2	0.8	0.8	0.2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Table 3. Fuzzy diagnoses for assembly: control valve- servomotor-positioner (example 1)

FS	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{18}	f_{19}
Minimum approach	0	0	0	0	0	0	0	0	0.4	0.6	0	0.4	0	0.1	0.4	0	0	0	0
Multiplicative approach	0	0	0	0	0	0	0	0	0.29	0.43	0	0.29	0	0.05	0.29	0	0	0	0
Additive approach	0.55	0.55	0.28	0.72	0.38	0.28	0.38	0.72	0.85	0.88	0.47	0.85	0.55	0.75	0.85	0.38	0.38	0.38	0.38
Mixed approach	0.46	0.46	0.24	0.60	0.32	0.24	0.32	0.60	0.72	0.74	0.39	0.72	0.46	0.63	0.72	0.32	0.32	0.32	0.32

Table 4. Fuzzy symptom conformity table and diagnosis for assembly: control valve- servomotor-positioner (example2)

FSS	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{18}	f_{19}
s_1	1	1	1	1	1	1	1	1	0	0	1	0	1	0	0	1	1	1	1
s_2	1	1	0	1	0	0	0	1	0	1	0	0	1	1	0	0	0	0	0
s_3	1	0	0	1	0	0	0	1	1	1	1	1	0	1	1	0	0	0	0
s_4	1	0	0	1	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0
s_5	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
s_6	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 5. Fuzzy diagnoses for assembly: control valve- servomotor-positioner (example 2)

FS	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}	f_{15}	f_{16}	f_{17}	f_{18}	f_{19}
Min. approach	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Mult. approach	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Additive approach	0.83	0.67	0.33	1.00	0.50	0.33	0.50	1,00	0.50	0.67	0.83	0.67	0.83	0.67	0,50	0.50	0.50	0.50	0.50
Mixed approach	0.42	0.33	0.17	0.50	0.25	0.17	0.25	0.50	0.25	0.33	0.42	0.33	0.42	0.33	0.25	0.25	0.25	0.25	0.25

Example 2:

Consider the particular set of current fuzzy symptoms equal to crisp three-valued set obtained from diagnostic signals set given in example 1 by rounding the set entries to integer values:

$$S = \{s_1=\{0, 1, 0\}, s_2=\{0, 1, 0\}, s_3=\{1, 0, 0\}, \\ s_4 = \{0, 1, 0\}, s_5=\{1, 0\}, s_6=\{1, 0\}\}$$

The τ_{jk} values (fuzzy symptom conformity table with references given in table 4) in this case are binary valued. Diagnosis is shown in table 5.

4. SUMMARY

For the actuator fault isolation the fuzzy techniques and information system theory was applied. The four simple fuzzy fault isolation approaches are presented. These approaches allows considering symptoms uncertainty and real time applicability. The approaches are characterised by immune factors against measurements noise. The greater immunity factors, the more diluted or "flatness" diagnosis can be observed.

Because of simplicity and fastness, presented above diagnostic algorithms for final control are useful for application in on-line diagnostics performed in supervisory control and diagnosing systems as well as in the smart actuators. To make the fault detection and isolation algorithms sufficiently effective the availability of the majority of considered measurements must be ensured. If it is not a case the isolation quality appropriately decreases.

It is also possible to run all approaches parallel and building decision making algorithm basing on evaluation of all diagnosis achieved.

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