

## QUALITATIVE CONTROLLERS : QUALITATIVE APPROACH TO FAULT DETECTION & DIAGNOSIS OF INDUSTRIAL CONTROLLERS

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### ABSTRACT

In this paper we use the Qualitative Control (QC) formalism [4] to detect, diagnose and reason about the malfunction of industrial controllers. The qualitative fault detector begins with a proper setting of the parameters in the form of rules describing the behavior of the system. The method searches for a faulty part, toggles the set points one at a time and decides upon the cause of the conflict in order to explain the discrepancy between the observed and predicted behavior.

### Key Words :

Qualitative reasoning, Intelligent control, Flow graph, Constraint network, Qualitative Control, Diagnosis.

### 1. INTRODUCTION

Artificial Intelligence (AI) is an attempt to find the process models that account for all kinds of human behavior [1]. Fault detection and diagnosis are among those behaviors. AI provides some new techniques for this purpose. Qualitative fault diagnosis is built upon the Qualitative Control (QC) [4] formalism. QC is a formalism to reason about the behavior, synthesize the desired behavior and reason about malfunction of the physical systems. QC is the extension and elaboration of the Qualitative Reasoning (QR) technique [3,7,14]. In QC the plant's structure is organized into a set of structural modules, then replaced by the qualitative model in the form of a Constraint Network [2]. The processes [5] are identified and the QR derives the behavioral information. QC takes a given desired behavior and can synthesize it or decide upon the control. For a given behavior, QC exploits the RA and MRA techniques to cope with the shape of the desired behavior and reason about the changes of the parameters, input conditions and speed of the processes. The most important advantage of the QC over the previous formalisms is the ability to handle both the numeric and symbolic information and discrete and continuous processes in a mixed structure within a unified modeling environment. Continuous processes are modeled in the form of Qualitative Flow Graph (QFG) [4] and discrete processes are represented by Extended State Machines (ESM) [8]. The conventional plant-controller picture is reproduced by two CNS interacting through Control Patterns (CP). The QC techniques can cope with the sudden structural modifications and degradation of the system therefore applicable in reasoning about

malfunction. In qualitative diagnosis naturally both continuous and discrete changes are possible to occur.

The structure of the paper is as follows: In section 2 we discuss briefly about QC and its modeling constructs. Section 3 will talk about the qualitative supervisory control and in section 4 the QC is used to detect faults in a detailed worked out example. Section 5 explains the achievements and suggests some further problems yet left to be solved.

**2. QUALITATIVE CONTROL (QC)**  
Constraint Networks (QFG and ESM) is the modeling object and Relativity Analysis (RA) is the reasoning tool in QC. In what follows we talk about them briefly.

#### 2-1. Constraint Network

The Constraint Network (CN) is the picture of the situation and it is the body of the processes. CN is a declarative structure which expresses relations among variables/activities. It consists of some nodes connected by constraints [2]. QFG is a CN whose nodes are qualitative variables and arcs are operations from the defined syntax operation set. ESM is another CN whose nodes are the activities and the arcs are events.

CN is synonymous to "language generator" (G) which is defined formally as an automaton. G is composed of five sets :

$$G = ( V , Z , d , V_0 , V_m )$$

In QFG V is the set of variables (v).

In ESM V is the non-empty set of activities (landmarks).

In QFG Z is the set of qualitative operations which show how the variables are related.

$$Z = \{ \text{DERIV, INTGL, M}^+, \text{M}^-, A \} .$$

In ESM Z is the set of predicates standing for the events or transition among the activities. Each event predicate denotes a rule [5] of the form:

$$Z : \{ \text{Condition} \rightarrow \text{Action} \}$$

Condition is any logic/analytic expression, when proved true, the action is enabled. Action is any change of data variables, synchronous communication among channels, or cooperation with a similar labeled activity in some other ESM.

d is the transition function. Each pair of {activity/variable, event/operation}

can produce another activity/ variable which will be the consequence or effect of transition.

$$d : Z \times V \text{ ---->} V$$

$$d(Z, V_1) = V_2 \quad \text{Def. } (Z, V_1, V_2)$$

In QFG  $v_o$  is the set of initial variables of the processes.

In ESM  $v_o$  is the set of initial activities.  
 $V_m$  is the marked variable/activity set which may represent a target.

### 2-2. Behavioral Fragment

The Behavioral Fragment (BF) is the record of the changes over time for each word of the language  $L(G)$  defined as:

$Z^*$ : Set of finite strings (S) of elements of Z.

Any subset of  $Z^*$  is a language over Z.

$$d : Z^* \times V \text{ ---->} V$$

where:  $d(1, V) = V$

$$d(SZ, V_1) = d(Z, d(S, V_1))$$

$$d(S, V_1) = V_2$$

$$V_1, V_2 \in V$$

The BF is represented by the track of the propagation of the external cause into the QFG when all other processes are supposed to be masked.

### 2-3. RELATIVITY ANALYSIS

QC has a multilevel hierarchical reasoner. While the CN encounters physical functions based on which, QR builds the knowledge in the generalized functional level [10]. RA and MRA use this information and derive further information in the abstract functional level. RA has a modified version (MRA) which concentrates on the relative speed of the processes. In MRA each node of CN is provided with some assertions on speed. The speed is deviated on the QFG according to the propagation rules which are propositions relating speed and time. One typical rule is given below.

```

*****
Landmark  Speed      Time
*****
          Rising trend dx/dt>0 :
          Faster  ---> Less time
Same      Slower  ---> More time
          Invariant ---> Invariant
          Falling trend dx/dt<0 :
          Faster  ---> Less time
Same      Slower  ---> More time
          Invariant ---> Invariant
*****

```

RA and MRA can reason about the direct effects of the inputs on the outputs, changes of the parameters on the behavior and effects of exploiting another processes in overlap way including changes of the initial condition. The advantage of RA and MRA is their capability to produce additional knowledge from a single simulation run [12,13].

### 3. QUALITATIVE SUPERVISORY CONTROL

In the previous section we introduced the QC formalism for the plant in the absence of an

external controller. In qualitative supervisory control we work with the systems of mixed structure. The structural constraints in mixed structures are not only the relations holding among the qualitative operations but also some kind of logic conditions. In qualitative supervisory control the basic idea is that the controller switches the control patterns. Here we can define the "controlled generator" ( $G_o$ ) which is a CN with controlled arcs. A controlled generator has multi-version graph due to the control pattern specified by the controller defined formally,

$$G_o = \{V, Z, d_c, v_o, V_m, K, CP\}$$

where:

$V, Z, v_o, V_m$  are as defined before;

$CP$  is the control pattern;

(for each operation due to the prescribed control the mask code is specified).

$$CP \times Z \text{ ---->} K$$

$$k(cp, z) = (-1, 0, +1)$$

$$d_c : K \times Z \times V \text{ ---->} V$$

$$d_c(k, z, v_1) = v_2$$

if  $d(z, v_1)$  is defined

and  $k(z) = 1$  or  $0$ .

( $z$  is enabled or insignificant)

Suppose that  $G_1, G_2, \dots, G_n$  denote (n) generators in a network with the same event/operation set (Z):

$$G_1 : (V_1, Z, d_1, v_{o1}, V_{m1})$$

$$G_2 : (V_2, Z, d_2, v_{o2}, V_{m2})$$

.....

$$G_n : (V_n, Z, d_n, v_{on}, V_{mn})$$

In [9] for a pair of generator-supervisor the direct state feedback is explained. Suppose that the pair  $G_j$  and  $G_i$  are the controller and the plant respectively, and suppose that there are (n) possible control strategies designated by the control pattern (CP).

$$CP_i = \{cp \mid cp = 1, 2, 3, \dots, n\}; \quad CP \in I$$

The state feedback function can be defined:

$$SF : Z \text{ ---->} CP_i$$

for each operation of the controller  $z_j \in Z$ , then:

$$cp_i = SF(z_j) \in \{1, 2, \dots, n\}$$

We can extend the concept of state feedback to the mutual state feedback in a network of generators. In mutual state feedback, for a pair of generators  $G_1$  and  $G_2$ , the  $G_1$ 's processes assign the control pattern of  $G_2$  ( $CP_2$ ) and in turn the masked QFG of  $G_2$  and  $G_2$ 's processes assign the control pattern of  $G_1$  ( $CP_1$ ). Finally, a single supervisory control (SSC) system composed of a pair of generators, is defined as:

$$SSC = \{V_1, V_2, Z, d_1, d_2, (v_{o1}, v_{o2}), V_{m1}, V_{m2}, CP_1, CP_2, K\}$$

where:

$$G_1 = \{V_1, Z, d_1, v_{o1}, V_{m1}, CP_1\}$$

is the plant generator;

$$G_2 = \{V_2, Z, d_2, v_{o2}, V_{m2}, CP_2\}$$

is the controller;

$CP_1$  and  $CP_2$  are the control patterns;

$K$  is the mask function;

### 4. QUALITATIVE FAULT DETECTION & DIAGNOSIS

In this section we use the QC to detect the faults in a physical system. Fault detection is

based on topological search strategy [15]. There are two possible strategies for fault detection: **Symptomatic** (experience based) search [11,15] and **Topological** (model based) search [11,15]. The symptomatic or experimental search method is based on the system's model of the malfunction and is efficient when facing the faults with a previous record. In this case there are some compiled data fragments in the form of symptom-cause) mapping heuristic rules. Even the most efficient symptomatic search algorithms, allowing parallel, nested and meta-search, fall when posed to the novel faults [6,15]. Topological search on the other hand depends on the model of the normal system and suitable for novel fault detection. Here no information on system's failure is available. The drawback of topological search is its slower speed compared with the symptomatic search.

We can formulate the problem of fault detection as one has information about the system's structure  $\Omega$  described in any logic and a set of predicted behaviors  $\Gamma$ . Then given some observed behavior set  $\Gamma^*$  the real behavior of the faulty system different from the set  $\Gamma$ . There are also some information about the possible abnormal functions of the components of the system  $\Psi$ . The problem is then describing the discrepancy between  $\Gamma$  and  $\Gamma^*$  in terms of  $\Psi$ . YOON et al. [15] has used the qualitative topological graph for  $\Omega$ , to simulate the behavior of the plant and detect the novel faults. In this paper we use the QFG for  $\Omega$  and the possible behavior set  $\Gamma$  is composed of the BFs. Because of the quick interpretation of the results in the form of symptom-causes it is possible to derive the rules of malfunction simultaneously. Once a new fault is detected it can be recorded in the form of a rule for future symptomatic search.

Fig.1 shows the double fuel tank example which is a simple version of the OBS (orbital refueling system) [15]. The fuel can be pumped from one tank to the other due to the pressure differences of the tanks. The control tools are the valves  $V_{11}$ ,  $V_{12}$ ,  $V_{21}$ ,  $V_{22}$  and  $V_3$ .

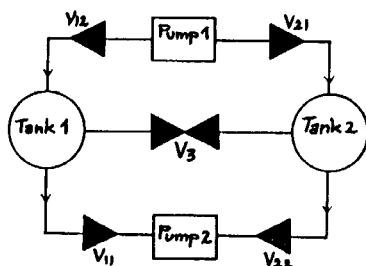


Fig. 1 : The simplified OBS system

Fig.2 shows the QFG for this plant. Some of the events in this graph are controlled events standing for the discrete changes. The possible landmark points are those when the fuel in the tanks get to zero or full.

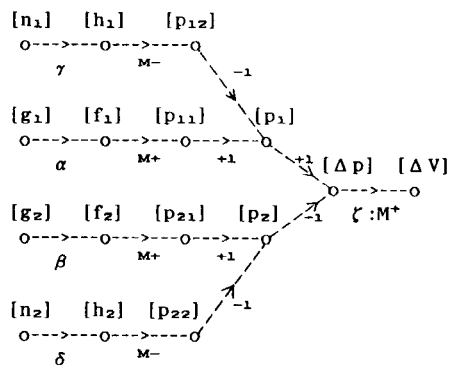


Fig. 2 : The QFG of the simplified OBS system

Here there is the set of qualitative equations. Conditional events are denoted by predicates  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$  and  $\zeta$ .

$$\begin{aligned}
 [f_1] &= [g_1] && ; \text{ If } V_{22} \text{ open } (\alpha) \\
 [f_2] &= [g_2] && ; \text{ If } V_{21} \text{ open } (\beta) \\
 [h_1] &= [n_1] && ; \text{ If } V_{11} \text{ open } (\gamma) \\
 [h_2] &= [n_2] && ; \text{ If } V_{22} \text{ open } (\delta) \\
 [p_{11}] &= M^+[f_1] && ; - \\
 [p_{12}] &= M^-[h_1] && ; - \\
 [p_{21}] &= M^+[f_2] && ; - \\
 [p_{22}] &= M^-[h_2] && ; - \\
 [p_1] &= [p_{12}] - [p_{11}] && ; - \\
 [p_2] &= [p_{21}] - [p_{22}] && ; - \\
 [\Delta p] &= [p_1] - [p_2] && ; - \\
 [\Delta V] &= M^+[\Delta p] && ; \text{ If } V_3 \text{ open } (\zeta)
 \end{aligned}$$

The inhibitive conditions are that the valves  $V_{21}$  and  $V_{12}$  or  $V_{11}$  and  $V_{22}$  are not allowed to be open simultaneously. As for the set  $\Psi$ , the abnormal functions of the valves are either leakage when closed or gripped when opened. For the first approximation suppose that the valves are binary. Then if the predicted function of a valve is  $p$ , when it is faulty it shows the  $p'$ :  $p' = \text{NOT } p$ .

The qualitative fault detector begins with a possible operating word, that is the correct setting of the parameters. The operating word is given by the rules describing the behavior of the system. There are two sets of behavioral rules in this example:

- $\Pi_1$ : ( $\delta$ :  $V_{22}$  open) & ( $\beta$ :  $V_{21}$  closed)  $\rightarrow$  pressure drop in  $T_2$ .
- $\Pi_2$ : ( $\alpha$ :  $V_{12}$  open) & ( $\gamma$ :  $V_{11}$  closed)  $\rightarrow$  pressurize  $T_1$ .
- $\Pi_3$ : ( $\zeta$ :  $V_3$  open)  $\rightarrow$  fuel transfer from  $T_1$  to  $T_2$ .
- $\Pi_1'$ : ( $\beta$ :  $V_{21}$  open) & ( $\delta$ :  $V_{22}$  closed)  $\rightarrow$  pressurize  $T_2$ .
- $\Pi_2'$ : ( $\gamma$ :  $V_{11}$  open) & ( $\alpha$ :  $V_{12}$  closed)  $\rightarrow$  pressure drop in  $T_1$ .
- $\Pi_3'$ : ( $\zeta$ :  $V_3$  open)  $\rightarrow$  fuel transfer from  $T_2$  to  $T_1$ .

The operating words are the possible settings of the controlled valves.

- ①.  $\alpha \beta \gamma \delta \zeta$ : fuel transfer from  $T_1$  to  $T_2$ ;
  - ②.  $\underline{\alpha} \underline{\beta} \underline{\gamma} \underline{\delta} \underline{\zeta}$ : fuel transfer from  $T_2$  to  $T_1$ ;
- Suppose that an observed behavior says that for the initial setting ①, there is no sign of fuel transfer from  $T_1$  to  $T_2$ , or in qualitative terms:  $[\Delta V] = 0$ . The qualitative reasoner will

use the QFG to reason backwards:

$\zeta$

$[\Delta V]=0 \text{ ---->} [\Delta p]=0$   
Possible malfunction:  
 $\zeta \text{ ----> NOT } \zeta$ , i.e.  $V_3$  is gripped.

otherwise:

$[\Delta p]=0 \text{ ---->} [p_1]=[p_2]$   
 $[p_1]=[p_{11}]-[p_{12}]$   
 $[p_2]=[p_{21}]-[p_{22}]$   
 $[p_{12}]-[p_{11}]=[p_{21}]-[p_{22}]$   
 $[p_{12}]=M^-[h_1]$  AND  $[h_1]=[n_1]$   
IF  $V_{11}$  open ( $\gamma$ )  
 $[p_{11}]=M^+[f_1]$  AND  $[f_1]=[g_1]$   
IF  $V_{12}$  open ( $\alpha$ )  
 $[p_{21}]=M^+[f_2]$  AND  $[f_2]=[g_2]$   
IF  $V_{21}$  open ( $\beta$ )  
 $[p_{22}]=M^-[h_2]$  AND  $[h_2]=[n_2]$   
IF  $V_{22}$  open ( $\delta$ )

a. In case of all valves working correctly:  
( $V_{12}$  open) and ( $V_{22}$  open), therefore:

$[p_{12}]=0$   $[p_{21}]=0$   $[p_{11}]=[p_{22}]$

From the QFG In this case we have that:

$[p_{22}]+[p_{11}]=[\Delta p]$

this is a conflict because:  $[p_{12}]=[p_{21}]=0$ .

When facing a conflict, then its initial causes are to be checked. In this case we have two choices and for each choice we should do further reasoning:

①.  $\alpha \text{ ----> NOT } \alpha$  ;

$V_{12}$  closed ---->  $[p_{11}]=0$  AND  $[p_{22}]=[\Delta p]=0$   
This implies that  $V_{22}$  must also be closed.  
This means that one possible fault is both valves  $V_{12}$  and  $V_{22}$  are gripped.

②.  $\delta \text{ ----> NOT } \delta$  ;

$V_{22}$  closed ---->  $[p_{22}]=0$  AND  $[p_{11}]=[\Delta p]=0$   
This implies that  $V_{12}$  must also be closed.  
This means that again one possible fault is both valves  $V_{12}$  and  $V_{22}$  are gripped.

b. In case of one faulty part there are two possibilities:

①. Suppose that  $\text{NOT } \gamma \text{ ---->} \gamma$ ; then:

$[p_1]=[p_{11}]-[p_{12}]$   
 $[p_2]=-[p_{22}]=[p_{11}]-[p_{12}]$  ; which is a possible formula. Therefore one possible explanation is that the valve  $V_{11}$  is leaking.

②. Suppose that  $\text{NOT } \beta \text{ ---->} \beta$  ; then:

$[p_2]=[p_{21}]-[p_{22}]$   
 $[p_1]=-[p_{11}]=[p_{21}]-[p_{22}]$  ; which is a possible formula. Therefore one possible explanation is that the valve  $V_{21}$  is leaking.

Finally we can summarize the results of fault detection for the behavioral word  $\alpha \beta \gamma \delta \zeta$  :

- ①. Valve  $V_3$  is possibly gripped;
- ②. Valves  $V_{12}$  and  $V_{22}$  are both gripped simultaneously;
- ③. Valve  $V_{11}$  is leaking;
- ④. Valve  $V_{21}$  is leaking;

For the other behavioral word  $\underline{\alpha} \underline{\beta} \underline{\gamma} \underline{\delta} \underline{\zeta}$  the results are derived in the same way:

- ①. Valve  $V_3$  is possibly gripped;
- ②. Valves  $V_{11}$  and  $V_{21}$  are both gripped simultaneously;
- ③. Valve  $V_{12}$  is leaking;
- ④. Valve  $V_{22}$  is leaking;

Those possible faults common between a number of behavioral words are supposed to happen more frequently.

## 5. CONCLUSION

This paper introduced the applications of Qualitative Control (QC) formalism to detect and diagnose faults in industrial controllers. The qualitative fault detector begins with a possible operating word, that is the correct setting of the parameters. The operating word is given by the rules describing the behavior of the system. The method searches for a faulty part one by one, that is first assuming that all setting is correct and then changing only one of the set values at a time. When facing a conflict, then its initial causes are to be checked. The method tries to solve the conflict and explain the discrepancy due to the observed behavior. The method here is well suited to deterministic discrete faults as well as the continuous ones.

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