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QUALITATIVE CONTROL : QUALITATIVE DESIGN & VERIFICATION OF INDUSTRIAL CONTROLLERS

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ABSTRACT

"Smart Robots" working as controller (supervisor or operator) of industrial plants and processes are the center of concern in this paper. Here I introduce the preliminaries of a new formalism called "Qualitative Control" (QC), which can be used to reason about the behavior and synthesize the desired behavior of the system, resembling the problem solving behavior of human operators/supervisors. I use the qualitative flow graph (QFG) to represent the structural description and qualitative reasoning method [8] to derive the potential behaviors. Qualitative control begins with a given desired behavior and based on the knowledge on the potential behaviors, by exploiting the sequential and adjustment methods it can synthesize the desired behavior and decide upon the control. Furthermore, the relativity analysis (RA) and its modified version introduced in this paper allow inferences of the direct input-output forms and qualitative speed comparison of the processes. Some examples will show practical applicability of the suggested methods.

Key Words:
Qualitative reasoning, Flow graph, Process, Behavioral fragment, Synthesis, Relativity.

1. INTRODUCTION

The concept of control can be described as the process of influencing the behavior of a dynamic system so as to achieve a desired goal [5]. Robots working in controlling a plant in hazardous environments, should cope with the control problems in the same way as the human operator does. Therefore they should possess besides the domain knowledge, some rational reasoning method in order to integrate sensing with action.

Qualitative Control (QC) has its ground points in Artificial Intelligence (AI) and Cognitive Science, exploiting their rich literature under the general topic of "Qualitative Reasoning" (QR). Qualitative Reasoning [3,8] discusses about the behavior of physical systems and provides information on their behavior. QC on the other hand, begins with a given desired behavior and provides necessary or possible scenarios to get to that behavior based on the knowledge about the potential behaviors. One such example which I work it out through this paper is the liquid level control of a tank shown in Fig.1. The robot exploits some agents to perform the control function, when the final effect is not the direct consequence of those agents. Many practical regulator problems fall within this scope. From traditional control point of view these problems are not new, and some of them already implemented by analog/ digital controllers. Qualitative Control opens a new aspect : investigating the solution to the controller (regulator) problems by means of new methods compatible to the human-like cognition and reasoning.

What we call "knowledge" about a physical system is mainly categorized into the formal definite or compiled situation- specific data fragments on system's structure, behavior and function. There are two potential approaches for structural description of the system, namely: "device oriented" and "event oriented". And this can be the emerging point for the two versions of qualitative reasoning methods. The first approach is somewhat qualitative integral and differential calculus [3,6,8,9,15]. Qualitative reasoning works with a scenario of the situation which is in turn composed of acts (regions). Here one keeps track of two types of variables: global and local. Global variables represent the boundaries and local variables just represent the internal situation of the acts (regions). The qualitative simulation algorithm derives behavior from the structure and keeps track of the causal changes of both global and local variables. Kuipers [8,9], DeKleer [3,4], Forbus [6], Williams [15] and some other researchers have proposed some versions of qualitative reasoning algorithms.

2. QUALITATIVE CONTROL

Let's think about an intelligent robot assigned to control a system. It is supposed that our robot is provided with a domain oriented knowledge-base and also it has access to environmental information through its proper sensory organs. Such a robot will face the following problems at the outset:

1. How this system under study works ? (system's potential behavior and function)
2. Which strategies should be selected to meet the desired specification? (control strategy)

Human expert can handle these problems easily, because he uses his "common intuition" with the aid of some formal knowledge, informal heuristics and analytic tools. The answer to the first question is already found in some previous research works [8,3]. In this paper I concentrate on the second problem. The method is straightforward: once the system's structure is organized through a set of structural modules and their immediate interaction with the successive ones, on the next step each block is replaced by its qualitative model and the Qualitative Simulation algorithm (QS) is used to obtain the behavioral information. QC gets one such behavior and finds possible scenarios for control. QC is mainly composed of two parts:

a. Sequential Synthesis method to copy the shape of the desired behavior.
b. Adjustment method to reason about the input/ output relations, relative speed of the processes and the effects of initial conditions and controllable variables.

The concepts of process, phase, Qualitative Flow Graph (QFG) and Behavioral Fragments (BF) are central in this paper. First the QFG is derived and processes are recognized. Standard BFs for each process are derived and are used for further synthesize. Sequential Synthesizer puts the BFs together to copy the shape of the desired behavior. For reasoning about the speed of the processes one may have three choices: adjusting the controllable variables, exploiting another process in an overlap manner and changing the initial conditions. For all the Relativity Analysis will provide appropriate decisions. Table 1 summarizes the algorithms.

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Table 1 . QC algorithms

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Given information :

a. System structure in the form of structural blocks (naive representation).
b. Desired behavior of the system.

1. Replace each block by its qualitative model.
2. Exploit QS qualitative simulation algorithms to derive the potential behaviors.
3. Derive the Qualitative Flow Graph (QFG) of the system.
4. Derive the Behavioral fragments.
5. Exploit Serial Synthesis method to derive the desired behavior.
6. Exploit Adjustment method to reason about relative speed and disturbances.

****

3. QUALITATIVE FLOW GRAPH (QFG)

In Qualitative Control the structure of the working model and operations are modified version of the Kuipers' [8,9], that is, the mechanisms are transformed to qualitative form by means of the differentiation, addition, inversion, and monotonic functions called "syntax operation set" (Z). The novel point is that the set of algebraic qualitative equations then are represented in the form of "Qualitative Flow Graph" (QFG) which is a conceptual causal graph [12] representing the causal relation among the variables.

QFG is a directed graph whose nodes are qualitative variables and arcs are operations from the basic syntax operation set. QFG is a signal flow graph in the general sense of mathematics because it depicts the relation among a number of qualitative variables. On the other hand QFG is a causal flow graph [4,7] as in AI terminology because its directed arcs show the causal relation among variables.

For the example that I work it out in this paper the equations exhibiting the mechanisms are given below and the QFG is given in Fig. 2.

[F1] = K1 [r1]	[U] = INTGL [F]
[F2] = K2 [r2]	[V] = [U] + [Vo]
[F] = [F1] - [F2]	[h] = M+ [V]

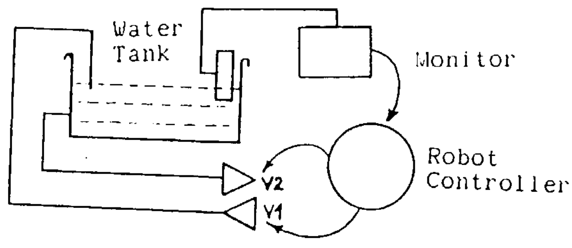


Fig. 1 : Liquid level control example

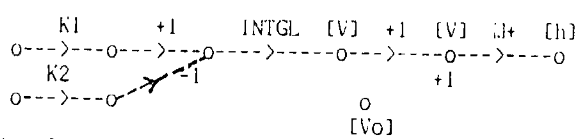


Fig. 2 : Qualitative Flow Graph of the liquid tank example.

4. PROCESS, PHASE & BEHAVIORAL FRAGMENT

"Process", "phase" and "Behavioral Fragment" (BF) concepts are central in QC. All physics is composed of processes and transition among them called phase change. In QC process is composed of a series of events activated by a cause -generally in the form of a change- due to the propagations of its effects on QFG. The cause always affects the first node and will be propagated to the following nodes due to the structural connections. In the previous works the process concept was implicit within the guidelines of continuous inference among a set of rules. Forbus [6] and Weld [14] have referred to process as some kind of rule with conditions and consequences and Williams [15] has proposed a reasoning method called "transition analysis" to keep track of the phase changes. Here I define the process as a directed trajectory on the QFG. In this sense each structural rule is represented by a node on QFG that relates the causes to the consequences. In the liquid tank example the processes are:

```
         K1        1       INTGL       +1        M+
P1: o--->---o--->---o--->----o--->----o--->----o
   [r1]    [F1]    [F]      [U]      [V]      [h]

         K2       -1       INTGL       +1        M+
P2: o--->---o--->---o--->----o--->----o--->----o
   [r2]    [F2]    [F]      [U]      [V]      [h]

                                       +1        M+
P3:                          o--->----o--->----o
                           [Vo]      [V]      [h]
```

DEFINITION 4-1. Behavioral Fragment (BF)

The behavioral fragment (BF_i) for the process P_i is the propagation of the external cause on the first node of P_i into the QFG when all other processes are supposed to be masked. Masking a process is equivalent to disable its trigger condition. The BF_i is denoted by the time graphs for all the nodes of that process (Fig.3). Possible BFs for our example are:

Input valve	Output valve	BFi
open	close	tank full (BF1)
close	open	tank empty (BF2)
close	close	no change (BF3)

Behavioral fragments can be used to synthesize the desired behavior of the system, by means of the following propositions and lemma.

PROPOSITION 4-2. Properties of BF

Behavioral Fragments (BFs) are intrinsic characteristics of the system. Once the behavioral fragments are identified, they are not subject to change, unless the system's structure is changed.

The intuition behind this proposition is that first, as there is no interference of behaviors and the neighboring processes are not active simultaneously, therefore BFs can be treated as ortogonal unit vectors in an N-dimensional space (due to N processes).

PROPOSITION 4-3. Input/Output Relation

The final consequences of the behavioral fragments due to reasonable inputs [9] are the same at least after a long period of time.

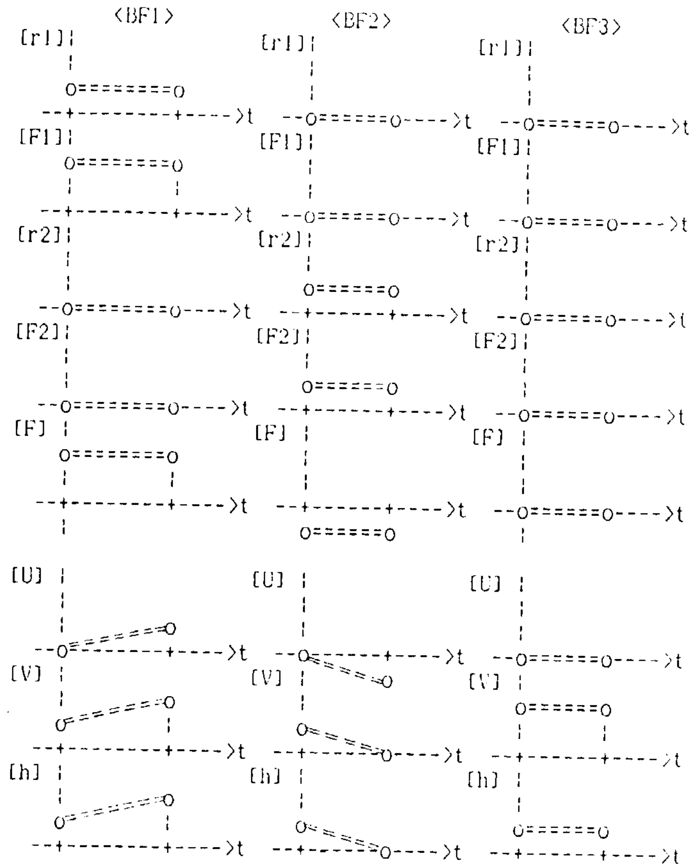


Fig. 3 : BFs of the liquid tank example

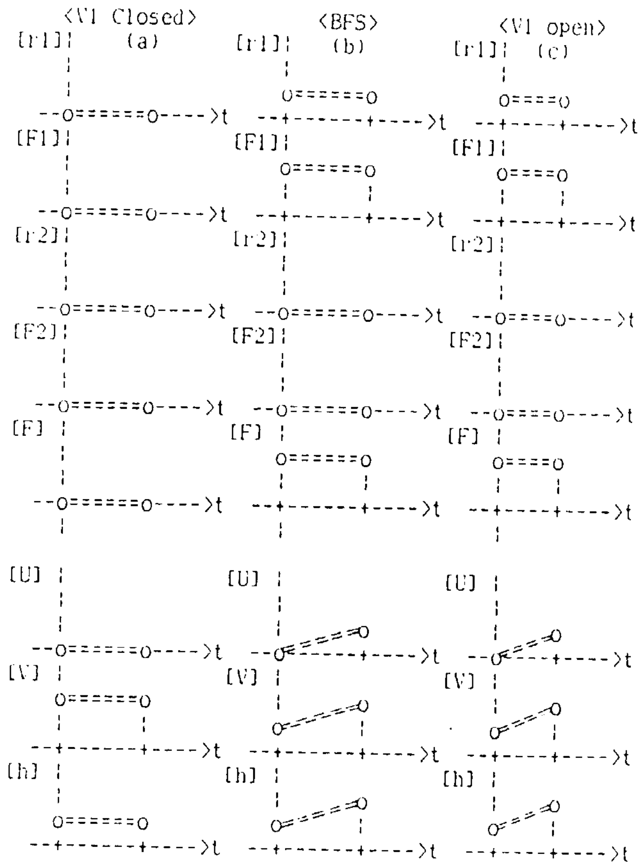


Fig. 4 : Standard Behavioral Fragment

The final consequence of a BF is the interpretation of the distinguished time points of the last node of the process. This proposition states that for example whatever the shape of the input signal of the process P1 is (provided being reasonable), the tank will finally become full.

DEFINITION 4-4. tandard Behavioral Fragment (SBF)
SBF is the BF due to the medium value of the initial cause (control variable).

The BF can be produced for some arbitrary values of the controllable variables. Generally those important values are minimum, maximum and medium (or minus, zero and plus). While the minimum and maximum values are useful in exaggeration analysis [14], the medium value provides the user with information about the real working condition of the process. In our example for each process, three values of valve closed, half open and full open are considered and their corresponding BFs are recorded off-line by simulation runs. Fig. 4 shows the BF1 due to 3 set points (a), (b) and (c) of the control variable. The (b) case is considered as standard.

5. DESIRED BEHAVIOR SYNTHESIS

From control point of view disjunctive and neighboring processes bring about no serious problem. Disjunctive processes can be checked only for temporal crossover perhaps in a way similar to the work of Thistle and Wonham [13]. I argued that the overall behavior of the system then can be derived from serial or parallel combination of those behavioral fragments. Synthesis of the desired behavior can be performed in two steps: First, "Sequential Synthesize" which tries to imitate the shape, and second, "Adjustment" which relies on the "Relativity Analysis" formalism and concentrates on adjustment of the speed of the processes. A method of synthesizing the desired behavior based on behavioral fragments of neighboring processes is introduced as the simplest case. Imitating the shape is not the only problem of concern and in many cases adjustments of speed to meet the temporal conditions is necessary. For such purpose I have developed the Relativity Analysis to reason about the following cases:

a. Reasoning about the effect of input on the output.
b. Effects of the changes of the control variable on the behavior.
c. Effects of exploiting another processes in overlap way (including changes of the initial condition).

5-1. Sequential Synthesis

In this step, the order of activating processes is the only matter of concern. Here one can breakdown the desired graph into some regions with identified BFs and activate their relevant processes sequentially. The following lemma explains the method.

LEMMA 5-1. Sequential Synthesis
The behavior of a system can be synthesized from the behavioral fragments of the neighboring processes serial, i.e. exploiting them one after another to get to the desired behavior.

An example will explain this idea clearly. Let's think that the required behavior of the liquid tank is given in Fig. 5. In this example for R1 we have got the BF1. For R3 we have the BF2 and for R2 and R4 we have the BF3 behavioral fragments. Therefore the required control in the sequential step will be: in R1 activate the process P1 (open the inlet valve). In R2 mask the same process (close the inlet valve). In R3 activate the process P2 (open the drain valve) and in R4 mask P2 (close the drain valve).

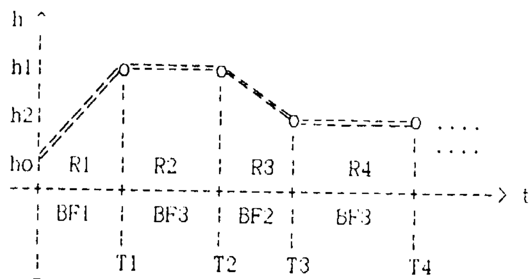


Fig. 5 : Desired behavior of the liquid tank

Therefore the control process then will be:

```
open V1-+->close V1-+->open V2-+->close V2-+-> ....
        |           |          |           |   ....
  R1--->|<----R2--->|<---R3--->|<----R4--->|   ....
```

In slow systems where the distinction between the time points is not critical, i.e. no serious limitation on the speed of the processes, the above step is sufficient to produce the desired behavior at least after considerable long time. The following sections explain the formalism and method of how one can play with this raw synthesized graph to grade up the performances.

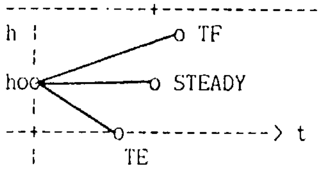
5-2. Relativity Analysis (RA)

Human being in daily life produces some sort of propositions such as:

"If I open the inlet valve, the tank will become eventually full".
"If I open the drain valve, the tank will become eventually empty".
"If I open both valves, the tank may either become full or empty. I can not exactly say what happens unless further information is available".

In the previous sections I intentionally ignored the possibility of one more other case of system behavior concerning the third proposition: when both valves are open simultaneously. Fig. 6 shows the possible behaviors in this case.

Input valve	Output valve	Behavior
open	open	tank full or empty :



F1>F2: eventually TF
F1=F2: STEADY
F1<F2: eventually TE

Fig. 6 : Possible final behaviors

These types of propositions relate an initial fact to a final event when there is no intermediate relation visible between them. This type of reasoning requires knowledge on the structure (i.e. QFG) and potential behaviors of the system (i.e. BFs) and moreover, a method that can deviate the effects of an initial fact to the final outcomes due to their relative values. Weld [14] has given an interpretation of relativity in terms of perspectives. I have developed the Relativity Analysis for the QFG by tracking and interpreting the zero crossovers of its summation nodes. Roughly speaking, once the BFs are distinguished, they are deviated through the QFG until an S-node where the input causes are evaluated and the dominant behavior is distinguished. The result of the relativity analysis is some propositions about the ultimate behavior of the system due to inputs (controllable variables). The RA method can be modified to reason about the relative speed of the processes (in terms of slower, faster or invariant compared to the relevant BFs). Relativity analysis and its modified version can answer the problems due to the initial conditions, change of the control variable and overlap of processes.

PROPOSITION 5-2. Uniqueness of Function & Behavior
The function of a node and the dominant behavior are fixed within an interval (i.e. between two distinguished time points), but can possibly change on transition among intervals.

PROPOSITION 5-3. Behavior of Temporal Intervals
For an S-node the interval on the time graph exhibits one and only one of the BFs of the system. The proof is straightforward due to the continuity principle.

LEMMA 5-4. Prediction of Possible Behavior

a. The BF for each process is pushed forward on the QFG for all initial nodes of the processes.
b. Depending on the relative values of the variables on the S-nodes the behavior branches.
c. For the intervals limited to the zero crossover points of the S-nodes' behavior, the dominant behavior is the one having the bigger absolute value.
d. The effect of the dominant process is also pushed forward on the QFG until the final nodes.

For the water tank example, suppose that the shapes of the graphs [F1] and [F2] are as shown in Fig. 7. This information and knowledge on the potential BFs is sufficient to reason about the final effect, i.e. the level of water in the tank. The Qualitative Simulator is required to produces the behavior of the S-nodes and their preceding nodes only. To the first approximation it produces the behavior of [F]. For the interval terminated to the point T1 where the first zero crossover is detected. Lemma 5-4 implies that the dominant behavior is BF2 (eventually Tank Empty) and for the next interval the dominant behavior is BF1 (eventually Tank Full). Further reasoning about node N5 is required to get to the final possible behavior as the second approximation. For node N5 it is suggested that for the interval terminated to T1, if the absolute value of V1 is bigger than Vo, then still the BF2 is the dominant behavior and the tank will become empty finally. Otherwise, the BF3 dominates and the level will remain steady. For the next interval beginning from T1, the reasoner compares V1 and Vo. If there is no zero crossover, the previous proposition on Tank Full will be valid. In case of zero crossover at time point T2, the reasoner will deduce that till

T2, BF3 dominates and from that point BF1 is the dominate behavior.

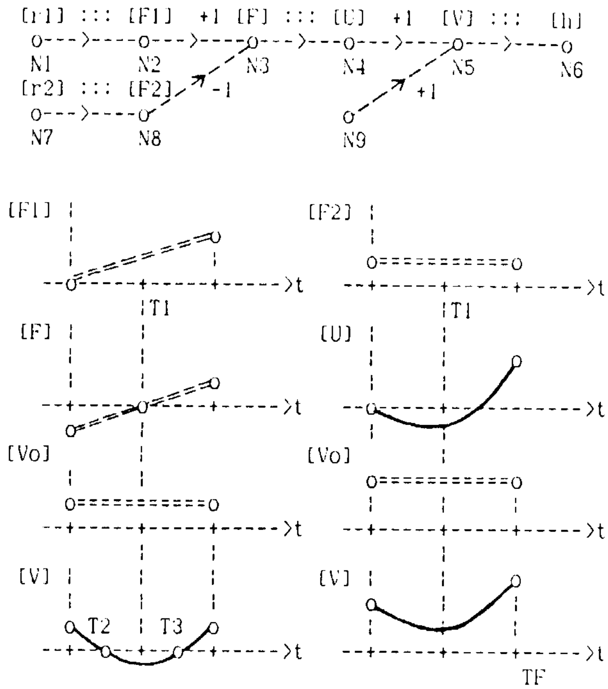


Fig. 7 : The results of Relativity Analysis

5-3 . <u>Modified Relativity Analysis (MRA)</u>

Temporal reasoning is another problem of concern in QC. Temporal reasoning in AI is considered in a number of previous works (such as [1,10,11]). Problems identified in temporal reasoning generally require a remarkable effort to be solved [11]. Intuitively, by comparing the speeds of processes qualitatively one can reason about distinguished time points implicitly. The trick is that instead of temporal tracking of the processes, in the form of histories, I compare their relative speeds qualitatively (i.e. Faster, Slower or Invariant). Note that the terms "faster" or "slower" do not mean taking shorter or longer time, but they only denote the relative speed (i.e. rate of increase or decrease) of the processes. The advantages of such analysis is that it allows us to answer questions such as: "If both inlet and drain valves are open and finally the tank becomes empty (or full), does the whole operation takes shorter or longer time?"

In MRA besides the behavior, each node of QFG is provided with some assertions on speed. From speed point of view, for the intervals identified in the Relativity Analysis phase and for their dominant BFs the speed of the process is compared to the relevant behavioral fragments qualitatively. The relative speed has three qualitative values: Slower (S), Faster (F) and Invariant (I). The speed assertions are deviated from one node to the following nodes on the QFG due to qualitative summation of the relative speeds.

Here the S-nodes of QFG exhibit two different functions: attenuation and amplification. A S-node in the QFG has the attenuation function if its input signals have opposite signs in value and it has amplification function if its inputs have the same sign in value. Properties of the attenuation and amplification nodes are:

a. The effect of attenuation node is always slowing down the behavior. In other words the resulting behavior will always increase or decrease slower compared to the dominant behavioral fragment.
b. The effect of the amplification node is always speeding up the behavior. In other words the resulting behavior will always increase or decrease faster compared to each of the behavioral fragments.

The following lemma explains how one can reason about the speed of the processes.

LEMMA 5-5. <u>Relative Speed</u>
On each time interval for the attenuating and all its following nodes, the relative speed is Slower (S). For amplification and all its following nodes the relative speed is Faster (F). No Comment (NC) happens when a node is preceded by both attenuating and amplification nodes. For all the other nodes the relative speed is Invariant (I). The inferential rules of relative states due to the qualitative summation are:

slower (S)	+ slower (S)	= slower (S)
faster (F)	+ slower (S)	= no comment (NC)
invariant (I)	+ slower (S)	= slower (S)
faster (F)	+ faster (F)	= faster (F)
invariant (I)	+ faster (F)	= faster (F)
invariant (I)	+ invariant (I)	= invariant (I)

For the QFG of our example the result of MRA is:

Node	Possible Behaviors Due to RA	Relative State Due to MRA
N1	BF1	Invariant
N2	BF1	Invariant
N3	BF2 (T1)-->BF1 (TF)	Slower
N4	BF2 (T1)-->BF1 (TF)	Slower
N5	BF2 (T3)-->BF3 (T2)-->BF1 (TF)	No Comment
	BF3 (T1)-->BF1 (TF)	No Comment
N6	BF2 (T3)-->BF3 (T2)-->BF1 (TF)	No Comment
	BF3 (T1)-->BF1 (TF)	No Comment
N7	BF2	Invariant
N8	BF2	Invariant
N9	BF3	Invariant

The effect of initial condition [Vo] is to speed up the two other processes. It is visible that if Vo is zero, then two other possible behaviors due to overlap, are slower than the BF1 and BF2 in any case. The above example clearly shows how different processes affect each other and also the powerfulness of QFG and RA. The next section shows how to exploit the RA and MRA in adjustment method.

6. <u>ADJUSTMENT METHOD</u>

Adjustment is a method to adjust the shape and speed of a given process by means of amplify or compensate the mutual effect of concurrent processes, changes of the initial conditions, and control variables. In adjustment one exploits the amplification and attenuation properties of the summation nodes and introduces new S-nodes to the QFG to cover the right and left intervals of the desired value of the goal variable.

6-1. Change of Control Variable

Changes of the control variable fall within two categories: first, changes of the intensity, second, changes of the shape. In the first case, the shape of the behavior of all nodes are the same as the standard BF of that process, only different due to the speed. Changes of the intensity bring about problems such as: "What happens when the inlet (or drain) valve is opened twice as much as it is now?" In MRA changes of the input is equivalent to adding a summation node to the first node of the process. The change comes in the same form of input and MRA rules deduce the relative speed of the process under new conditions. The following example considers the P1 case when the inlet valve BF1 is opened "more" than the medium case, therefore MRA deduces that the speed is faster for all nodes.

```
[r1] +1 [R] ::: [F1]  +1 [F] ::: [U] +1  [V] :: [h]
 o--->---o--->----o--->---o--->---o--->---o--->--o
       /  N1        N2      N3      N4           N6
     /+1
    o
[C]
```

In case of changing of the shape of the input. Proposition 4-3 suggested that the final outcome of the process remains the same but the shape of the graphs of the nodes of QFG may be changed. In this case the QS will produce the behavior for all nodes and the MRA reasons about their speeds.

6-2. Initial conditions

Changes of the initial conditions is also similar to adding a summation node to any node of the process. The rest is applying RA and MRA rules to reason behavior's shape and speed. The following example compares the standard behavior of P1 and P2 when having an initial condition Vo.

```
    [r1] :: [F1] +1 [F] ::: [U]  +1 [V] ::: [h]
P1: o--->---o--->---o--->---o--->---o--->---o
    N1      N2      N3      N4    / N5      N6
                                /+1
                       [Vo]  o
                             N9
    [r2] :: [F2] -1 [F] ::: [U]  +1 [V] ::: [h]
P2: o--->---o--->---o--->---o--->---o--->---o
    N7      N8      N3      N4    / N5      N6
                                /+1
                       [Vo]  o
                             N9
```

Node	Behaviors Due to RA P1	Behaviors Due to RA P2	Relative State Due to MRA P1	Relative State Due to MRA P2
N1	BF1	***	Invariant	***
N2	BF1	***	Invariant	***
N3	BF1	BF2	invariant	Invariant
N4	BF1	BF2	Invariant	Invariant
N5	BF1	BF2	Faster	Slower
N6	BF1	BF2	Faster	Slower
N7	***	BF2	***	Invariant
N8	***	BF2	***	Invariant
N9	BF3	BF3	Invariant	Invariant

In the case of both changing the initial conditions and the input the relative speeds are summed up qualitatively. The two above examples show that the overlapping processes also can be treated in the same way and the s-nodes dominate the behavior.

CONCLUSION

This paper introduced the preliminaries of Qualitative Control (QC) which tries to imitate the problem solving behavior of human operators. It uses the qualitative flow graph (QFG) as the structural model and qualitative reasoning (QS) to derive the behavior. Then based on the sequential and adjustment methods it can synthesize the desired behavior and derive possible scenarios to get to it. As the QS generates a number of possible behaviors for the system, QC also produces one scenario for each behavior. QC looks promising for application areas such as diagnosis and supervisory control.

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