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Functional Reasoning, Explanation and Analysis: A Collective View and A Proposal

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The goals of this research are (1) giving a collective view of the functional reasoning (FR) research through identifying common core, formalizing underlying assumptions and defining problems to be tackled; (2) developing methods for deriving and explaining function of devices from a description of their structure and behavior using FR techniques; and (3) applying FR techniques to real world engineering problems such as design and diagnosis. First, a survey of FR theories and techniques is presented, common assumptions and basic problems are identified. Second, Qualitative Function Formation (QFF) technique is introduced. In QFF, a function concept is defined as an interpretation of a persistence or an order in the sequence of qualitative states, using trace of qualitative state vector derived by simulation on a qualitative model of a device. Finally, application and implementation of QFF in an experimental design system is demonstrated.

1. INTRODUCTION

Traditionally, FR theories and techniques have appeared in different branches of inquiry. In biology, FR has to find answer to problems such as explaining why an organ (e.g. heart) is in an organism (e.g. human's body) in terms of its contribution to the functionality of the whole organism [38, 30, 3, 35, 42, 8, 33, 31]. Also FR is supposed to identify the 'natural function' of an organ (i.e. heart for pumping blood) from a set of other possible functions (i.e. making heart sound, etc.). In engineering, FR is mainly used to differentiates between 'means' and 'ends', in order to explain why a component is used in a device in terms of its contribution to overall functionality of the device [22, 39, 32, 40, 13]. In AI, generating understandable and sound explanation of function of devices with reference to common physical laws is considered as an area of study in Qualitative Reasoning (QR) [6].

The focus of this research is on (1) surveying the FR research, from the AI perspective, identifying common core, underlying assumptions and defining problems to be tackled; (2) developing FR techniques for deriving and explaining function of a device from a qualitative description of its structure and behavior through systematic generation and reasoning with such a model at various level of abstraction; and (3) applying FR techniques to real world engineering problems such as functional design and diagnosis.

Qualitative Function Formation (QFF) technique is developed and implemented to verify the ideas [14, 16, 17]. Basic features of QFF and an implementation of it are introduced in the following sections.

The structure of this paper is as follows: Section 2 introduces the basic terminology, assumptions, problems and reviews selected FR techniques with focus on their underlying assumptions, problems addressed and achievements. Section 3 introduces the QFF technique. In Section 4 an example on application of QFF in functional design is given and Section 5 describes an experimental implementation of QFF. Finally, Section 6 summarizes the results and presents a handful of ongoing research problems.

2. BASIC CONCEPTS AND TERMINOLOGY

Functional Reasoning (FR), in its common sense use, enables people to reason about the presence and function of objects in a containing system, derive the purpose of the system and explain how it can be achieved[1] . FR

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[1] Functional reasoning is used to explain goal directed behavior of objects. Such explanation includes two components: causal and functional explanations [33]. Functional explanation accounts for: (a) the presence of a component in a system in terms of certain effects it has on that system; (b) functional explanation explains the *purpose* of a system in terms of its structure and behavior or functions of its components. (a) refers to an explanation of the presence of some component in the system in terms of its contributions or certain effects that the component produces in the system [33], or in terms of some capacity that the component has and contributes to the capacity of the containing system [8]. (b) addresses the traditional teleological process of *'means'* and *'end'* [1].

embodies a collection of theories and techniques, the definition of which constitutes the subject of this paper.

The term *function* has a multilateral spectrum of meanings. Plato and Aristotle were among the earliest philosophers talking about *function* by describing function of objects conferring to some *good*[2] . Later philosophers were engaged with explaining the design into nature by interpreting function in terms of teleological notions of *'means'* and *'ends'* [1].

Function of a system is usually mentioned along with its *behavior*, *goal* and *purpose*, with respect to system's inner and outer environments [37]. Also it has strong connections with the notion of making efforts to obtain a certain result (mainly in man-made objects), or a certain future event [5]. In the representational viewpoint of function, which is central in AI, function of a system is addressed with reference to intention[3] of humans [6]. This is guiding the main stream of FR research in AI, such as [12, 11, 32, 39, 40, 26, 24, 28].

2.1. Functional Reasoning in AI

Typical FR systems vary mainly depending on the area of study (i.e., common sense reasoning, planning, image understanding, fault diagnosis, computer aided design, etc.), ontological primitives, representation schemes of structure and functions, focus of study on a particular problems, etc. A survey on three categories of FR techniques and systems, i.e. *explanation based systems*, *planning and design systems* and *conceptualization systems* is given in [13] (see Figure 1).

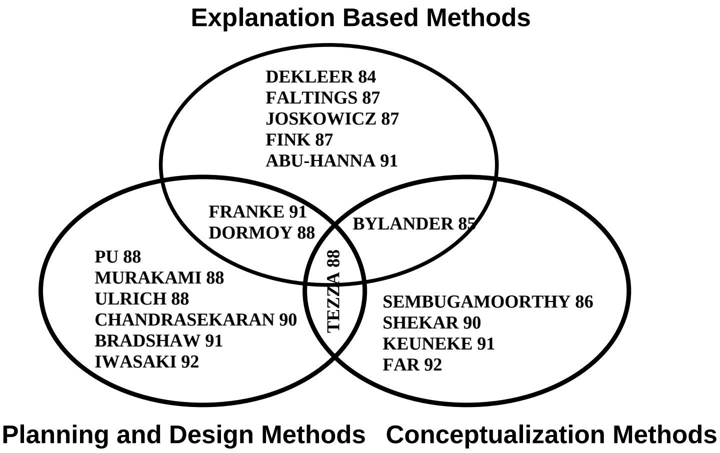

Figure 1. Functional reasoning techniques and systems.

Here we focus on FR as a branch of qualitative reasoning (QR) and concentrate on applications of FR in solving engineering design problems. Trace of FR in QR can be found along with the three major theories of qualitative physics. The *qualitative process theory* [19] influenced deriving function of mechanical objects using geometric data (see [12] in which a way of finding description of behavior of mechanical assemblies based on geometry of components is discussed), *qualitative confluence theory* [10] has influenced explanation of function of electronic circuits using mechanism graphs and teleological analysis (see [9]) and *qualitative simulation* [29] has led to explaining function of a device using scenarios and partial states (see [21]).

A main attraction of FR in engineering is supporting knowledge intensive activities of design. There are already some techniques considering functional design as their problem domain [36, 32, 34, 27, 7, 21, 25, 28].

2.2. Basic assumptions

The following assumptions are common to many FR techniques.

1. *Functionality in State Transition*: Any physical concept can be explained in terms of *histories* [23] and *states.* Intuitively, a history that leads to a function displays a certain pattern [5]. A basic feature of state representation is that it assigns a certain characteristic to its referred device [31], therefore it is possible to define function concepts with reference to discovery of an order in the state sequence. The key idea is that a function concept emerges from discovering a persisted state or an ordered pattern in a sequence of states. This is called '*functionality in state transition*'. In biological systems persistence is considered to be the most interesting characteristic and is believed to be governed by natural selection law. In man-made devices besides persistence other kinds of ordered patterns such as oscillation may also be considered.

2. *Functionality in Component Pair*: It seems that humans have a data base in which a device is associated with several functionalities. Some of the theories and systems have considered the function as a property

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[2] Even in some recent works function is connected with the notion of good, e.g. survival in a natural organism or efficiency in devices [38], or explaining function by its *usefulness* to the containing system.

[3] The term 'intention' is used in the narrow sense of a kind of plan that includes a representation of the object and its future effects.

of a single component of a device. However there are certain difficulties in both logical formulation (see for instance [42]) and actual implementation (see [39], etc.) of such theories. It is suggested that function can be ascribed to a pair of components instead of one (see [12, 20], etc.). This is called '*Functionality in Component Pair (FCP)*', stating that at least a pair of components are required to interact functionally[4] .

Without these assumptions it is difficult to derive different functions of a device and explain how it can have several functions.

2.3. Functional reasoning problems

We have identified four classes of FR problems [13]:

1. *Identification problem*: Given an object, explaining its function using knowledge of structure and behavior of its component and their organization. Typical works: [22, 9, 26, 39, 11, 12, 24].
2. *Explanation problem*: Explaining presence of a component in a containing system in terms of its contribution to the overall function of the system. Typical works: [30, 3, 35, 42, 8, 33].
3. *Selection problem*: Given a set of components, selecting the proper components that if used together can achieve a desired function. Typical works: [22, 34].
4. *Verification problem*: Verifying whether an object can exhibit a required function in a given situation. Typical works: [32, 40, 28].

3. QUALITATIVE FUNCTION FORMATION TECHNIQUE

(1) The qualitative model that we use in QFF is composed of a set of expressions involving three primitives: qualitative variables, ordinary- and coordinative- qualitative operations. Qualitative variables are counterpart of physical quantities, such as temperature and pressure, representing characteristics of the system's inner environment. Relation between the qualitative variables is defined by qualitative operations. Ordinary operations are monotonic increase (M^+), monotonic decrease (M^-) [29], positive influence (I^+) and negative influence (I^-) [19]. Coordinative operations account for interactive or protocol-based interactions, such as *'when'*, *'until'*, *'set'*, *'reset'*, and *'default'*. The qualitative model is a set of expressions of either of the following forms:

$$\begin{array}{lcllll} [Y] & = & O[X] & 'D' & [L_N^i] \\ [Y] & = & O[X] & 'D' & O[Z] \end{array} \tag{1}$$

$[Y], [X], [Z]$ and $[N]$ are qualitative variables. L_N^i is the ith landmark value of N. O is an ordinary qualitative operation. $O \in \mathcal{O}$,
$\mathcal{O} = \{M^+, M^-, I^+, I^-\}$
'D' is a coordinative operation (at this moment there are only 5 such operation, namely, *'when', 'until', 'set', 'reset'* and *'default'*).

1. 'when' operation: $[Y] = O[X]$ 'when' L_N^i; implying that $[Y] = O[X]$ only when the event L_N^i is present.
2. 'until' operation: $[Y] = O[X]$ 'until' L_N^i; implies that $[Y] = O[X]$ until the event L_N^i becomes absent.
3. 'set' operation: $[Y] = O[X]$ 'set' L_N^i; implying that $[Y] = O[X]$ only when setting $[N]$ to L_N^i.
4. 'reset' operation: $[Y] = O[X]$ 'reset' L_N^i; implying that $[Y] = O[X]$ only until resetting $[N]$ to L_N^i.
5. 'default' operation: $[Y] = O[X]$ 'default' $O[Z]$; implying that $[Y] = O[X]$, but only in case of $[X]$ absent, then $[Y] = O[Z]$.

The coordinative operations show a kind of data dependencies and can be processed in a different way than the ordinary simulation. Such dependencies can have only 4 possible types:

- *present* (±1): two events occur concurrently;

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[4] Close ideas are mentioned also by the Locality of Histories [23], Connectivity Hypothesis [20] and Pairwise Interaction of Parts [12].

- *absent* (0): two events do not occur concurrently;
- *true* (+1): an event has occurred;
- *false* (−1): an event has not occurred;

An algebra in which these 4 values can be represented by mod-3 integers is defined [4]. Every qualitative variable, denoted by upper case characters such as Ω_{CV_1}, has a pseudo- counterpart, denoted by lower case characters such as ω_{CV_1}, in this algebra. Each expression can be encoded in this algebra using *temporal-* and *dependency- constraints.* A temporal constraint assigns the value $(-1, 0, +1, \pm 1)$ to a pseudo-qualitative variable, depending on being false, absent, true, or present, respectively. A dependency constraint, on the other hand, derives the value for the related pseudo- qualitative variables as described in the model. Table 1 depicts the temporal and dependency constraints for the coordinative operations [13]. We will see later that only those ordinary operations that have their dependency constraint evaluated to (+1) can take part in the simulation [13].

Table 1
Temporal and dependency constraints

Expression	Temporal constraint	Dependency constraint
$[Y] = O[X] + O[Z]$	$y^2 = x^2$	$y^2 : [X] \to O \to [Y]$
	$y^2 = z^2$	$y^2 : [Z] \to O \to [Y]$
$[Y] = O[X]$ 'when' L^i_N	$y^2 = x^2(-n - n^2)$	$y^2 : [X] \to O \to [Y]$
$[Y] = O[X]$ 'until' L^i_N	$y^2 = x^2(-n)$	$y^2 : [X] \to O \to [Y]$
$[Y] = O[X]$ 'set' L^i_N	$y^2 = x^2(-n - n^2)$	$y^2 : [X] \to O \to [Y]$
$[Y] = O[X]$ 'reset' L^i_N	$y^2 = x^2(-n)$	$y^2 : [X] \to O \to [Y]$
$[Y] = O[X]$ 'default' L^i_N	$y^2 = x^2 + z^2(1 - x^2)$	$x^2 : [X] \to O \to [Y]$
		$z^2(1 - x^2) : [Z] \to O \to [Y]$

X, Y, Z and N are qualitative variables. x, y, z and n are their mod-3 values $(-1, 0, +1)$, respectively. L^i_N is the ith landmark value of the variable N.

(2) *Qualitative Flow Graph (QFG)* [14] is defined as a digraph embodying the qualitative model and temporal and dependency constraints. In QFG, nodes are qualitative variables and arcs are conditional ordinary qualitative operations, whose antecedents are dependency constraints. QFG shows indirect influences of qualitative variables. QFG is represented by 4 sets:

$$QFG = \{\mathcal{V}, \mathcal{A}, \mathcal{O}, \mathcal{C}\} \tag{2}$$

$\mathcal{V}$ set of nodes standing for the qualitative variables. $\mathcal{A}$ set of arcs relating the two nodes. $\mathcal{O}$ set of ordinary qualitative operations. $\mathcal{C}$ set of dependency constraints for coordinative qualitative operations given in Table 1.

All the arcs of the QFG are conditional. A conditional arc is:

$$A : C \to O \tag{3}$$

For each arc, $A \in \mathcal{A}$, if for $C \in \mathcal{C}, \mathcal{E}(C) = +1$, then $O \in \mathcal{O}$ is enabled.

$\mathcal{E}(C)$ is evaluation of the constraint C in mod-3.

(3) *Qualitative Processes (QPs)* are defined as finite, connected, unidirectional string of arcs of the QFG, relating an input node to an output one. An input node is the one with an in-degree zero. Similarly, an output node is the one with an out-degree zero.

A key point is distinguishing the effects of an input node on the network of the overlapping processes. Using the conventional notion of process in qualitative reasoning (such as [41] and [19]), for each process a number of possible behaviors can be generated and removing the ambiguity is not trivial [2]. In QFF processes are extracted from the QFG by decomposition, i.e. the merging nodes and the succeeding shared nodes and arcs between two processes are assigned to both. This is a requirement in QFF because the direct consequences of a certain process and its effect on the behavior of the whole system should be distinguished first, and then combined behavior of the process derived. This is where QFF departs from the main stream of the other qualitative techniques.

(4) *Behavioral Fragment (BF)* [14] is the characteristic behavior of a qualitative process and is defined as the record of landmark values for the displayed qualitative variables belonging to that process.

Behavioral fragment BF_{P_j} of a process P_j, is a finite sequence of landmark values (L_V^k), of the form:

$$BF_{P_j} = \{\forall V \in P_j \mid \quad (L_V^0, L_V^1, \ldots, L_V^n)\} \tag{4}$$

$$BF_{P_j} = \{\forall V \in P_j \mid \quad \biguplus_{k=0}^{n} (L_V^k)\} \tag{5}$$

L_V^k is the kth landmark value of the qualitative variable V, and $\biguplus$ is a symbol for abbreviating (4) to (5).

BFs are derived by qualitative simulation in two steps: (a) Dependency constraint satisfaction on the arcs of the processes. (b) Landmark value identification of the qualitative variables. First, the simulator looks for the antecedents of the conditional arcs that can satisfy the given situation. Through temporal and dependency analysis one can verify which of the arcs of the processes are activated, i.e. the mod-3 value of its dependency constraint is +1, and can take part in simulation. Then processes whose enabling conditions of their arcs are not yet satisfied are deleted and a conventional simulation program derives landmark values for each variable of the remaining processes. BFs are sequences leading to a function concept.

(5) A *Function* concept can be derived if a repetition cycle or an order (e.g. persistence, etc.) can be detected on BF sequences.

A function $\mathcal{F}$ has two attributes:

1. Operationality: the enabling conditions for the arcs of a process whose BF leads to the function.
2. Repetition cycle: for the behavioral fragment BF_{P_j} of the process P_j, the repetition cycle is a finite sequence of landmark values (L_V^k), of the form:

$$\mathcal{F} = \{\exists V \in P_j \mid \quad (L_V^i, L_V^{i+1}, \ldots, L_V^j) = S\} \tag{6}$$

$$\mathcal{F} = \{\exists V \in P_j \mid \quad \biguplus_{k=i}^{j} (L_V^k) = S\} \tag{7}$$

$\mathcal{F}$ is a function concept. S is a repetition cycle. i and j are indices for landmark values. If $i = j$, the cycle is a persistence. L_V^k is the kth landmark value of the qualitative variable V, and $\biguplus$ is a symbol for abbreviating (6) to (7).

The repetition cycle or persistence can be derived for each of the variables, therefore different cycles can possibly be detected and each cycle may represent a function concept from a different viewpoint. The function derived by QFF is a direct consequence of the user interacting with the network representation of the underlying physical model of the device and physical constraints. This is a very useful characteristic of the technique and can be used directly in functional design. Particularly, by recording the goal(s) of the user on each step and comparing it with the derived function, one can easily verify whether the arrangement can satisfy the intended goal(s) of the user.

4. FUNCTIONAL DESIGN USING QUALITATIVE FUNCTION FORMATION TECHNIQUE

Here is an illustrative example of a pressure tank system in an oil refinery, parts of which shown in Figure 2. We use QFF to identify function of the components (i.e. identification problem) and explaining why a component is used in the design (i.e. explanation problem). In this system, there are 4 tanks used to separate materials in a mixture of supplied material to T_2 through CV_6. For the sake of easier understanding let's consider a portion of the system composed of tanks T_1 and T_2. The core idea of the design in narrative form is:

> Pressure in T_2 is controlled by the settings of CV_4 and CV_5. The overall amount of the two phase material (material A and B) in T_2 is controlled by CV_1 and CV_2. The pressure in T_1 is controlled by CV_4. The level of material in T_1 is controlled by CV_1 and CV_3.

QFF is used to identify function of the objects (i.e. identification problem) and explaining why a component is used in the designed object (i.e. explanation problem).

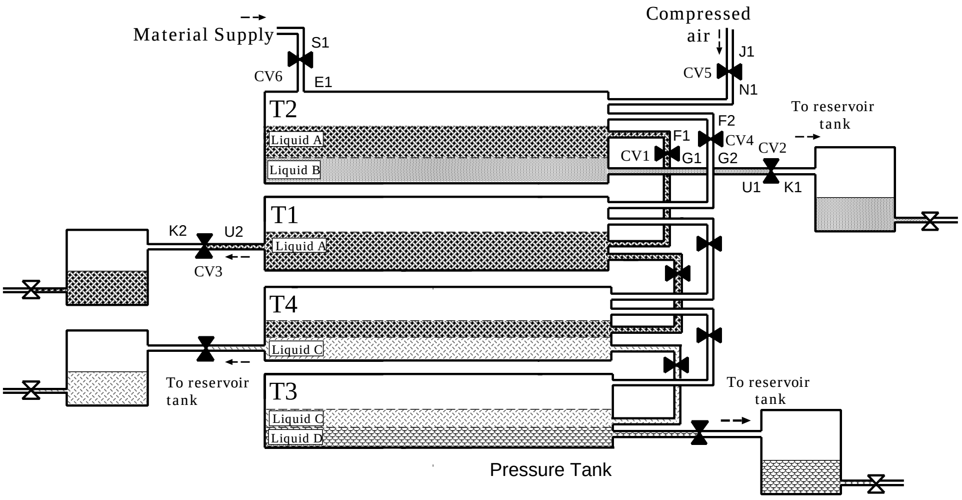


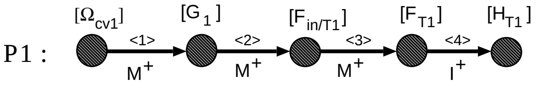
Figure 2. The pressure tank system.

4.1. Example 1: Identification of functions

This is a brief example showing how function of a pair of components can be derived from their qualitative model. Let's consider a portion of the system, composed of the object pair CV_1 and T_1. The relation between them is constrained by rules of flow and conservation besides the set points given by the designer,

$$\begin{array}{llll} [F_1] = [G_1] & = M^+[\Omega_{CV_1}] & 'set' & (\Omega_{CV_1} > 0) \\ [F_{in/T_1}] & = M^+[G_1] & 'set' & (\Omega_{CV_1} > 0) \\ [F_{T_1}] & = M^+[F_{in/T_1}] & & \\ [H_{T_1}] & = I^+[F_{T_1}] & & \end{array} \tag{8}$$

$[F_1]$ and $[G_1]$ stand for the flow-in and flow-out for the valve CV_1. $[F_{in/T_1}]$ is material flow-in for T_1. $[F_{T_1}]$ is the net flow and $[H_{T_1}]$ is the level of material in T_1. Temporal constraints are given below and dependency constraints are shown in Figure 3.



Dependency constraints		
$< 1 >$	:	$\omega^2_{CV_1}(-\omega_{CV_1} - \omega^2_{CV_1})$
$< 2 >$	:	$g^2_2(-\omega_{CV_1} - \omega^2_{CV_1})$
$< 3 >$	:	f^2_{in/T_1}
$< 4 >$	:	$h^2_{T_1}$

Figure 3. Dependency constraints for Example 1.

$$\begin{array}{ll} f_1^2 = g_1^2 & = \omega^2_{CV_1}(-\omega_{CV_1} - \omega^2_{CV_1}) \\ f^2_{in/T_1} & = g_1^2(-\omega_{CV_1} - \omega^2_{CV_1}) \\ f^2_{T_1} & = f^2_{in/T_1} \\ h^2_{T_1} & = f^2_{T_1} \end{array} \tag{9}$$

Qualitative process for this system is shown in Figure 3. Behavior of the component pairs can be derived, for the set point $(\Omega_{CV_1} > 0)$. In temporal constraint terms this means:

$$\omega_{CV_1} = 1 \tag{10}$$

By inserting its value in temporal constraints, one can derive that:

$$h^2_{T_1} = f^2_{T_1} = f^2_{in/T_1} = f_1^2 = g_1^2 = 1 \tag{11}$$

This means that conditions for the arcs of this process are evaluated to 1, implying that all the arcs are active and can take part in the simulation. Simulation results are:

$$BF_{P_1}:\quad \{(\Omega_{CV_1}>0)\rightarrow(F_{T_1}>0)\rightarrow(H^o_{T_1}<H_{T_1}\le H_{(T_1)max})\rightarrow(H_{T_1}=H_{(T_1)max})\} \tag{12}$$

This implies that the level of material in the tank will increase up to the maximum allowable level. The function of the pair (CV_1, T_1) can be derived using the cycle detection algorithm. Clearly the persistence in the level of material in the tank is detectable, therefore, the function of this pair is to maintain the level at the $H_{(T_1)max}$, that may be called $FULL$. Note that the term $FULL$ is just a reference term, whose functionally relevant meaning is described by the landmark value $H_{(T_1)max}$ for the pair.

$$FULL:\qquad H_{T_1}=H_{(T_1)max} \tag{13}$$

Similarly for the pair (CV_3, T_1) and for the set point $(\Omega_{CV_3}>0)$, one can derive that the level of material in the tank will decreases till the minimum level and the function of this pair is to make the tank $EMPTY$, described by,

$$EMPTY:\qquad H_{T_1}=H_{(T_1)min} \tag{14}$$

These definitions of functions are generated automatically and recorded in a proper frame.

4.2. Example 2: Explanation of functions

The reason for a component being selected to be a part of the designed system is explained in terms of its contribution to the desired function of the system. Again simulated behavior of the processes exhibits the way the components contribute to the functionality of the system.

Let's consider the system of Figure 2 and explain the why a given control valve, such as CV_2, is used in this design. The model embodying the valve CV_2 is:

$$\begin{array}{lcll}
[U_1] & = & M^+[\Omega_{CV_2}] & '\mathit{set}'\quad (\Omega_{CV_2}>0)\\
[H_{B/T_2}] & = & I^-[U_1] & '\mathit{set}'\quad (\Omega_{CV_2}>0)\\
[F_{out/T_2}] & = & I^+[U_1] & \\
[H_{T_2}] & = & M^+[H_{B/T_2}] & \\
[K_1] & = & [U_1] &
\end{array} \tag{15}$$

$[U_1]$ and $[K_1]$ are the flow-in and flow-out for CV_2 whose state variable is $[\Omega_{CV_2}]$. $[H_{T_2}]$ is the overall level of material in T_2. $[F_{out/T_2}]$ is the flow of material from T_2 and T_1, and $[H_{B/T_2}]$ is the level of B material in T_2. The temporal constraints are:

$$\begin{array}{lcl}
u_1^2 & = & \omega^2_{CV_2}(-\omega_{CV_2}-\omega^2_{CV_2})\\
h^2_{B/T_2} & = & u_1^2(-\omega_{CV_2}-\omega^2_{CV_2})\\
f^2_{out/T_2} & = & u_1^2\\
h^2_{T_2} & = & h^2_{B/T_2}\\
u_1^2 & = & k_1^2
\end{array} \tag{16}$$

CV_2 appears in three processes P_2, P_3 and P_4. Dependency constraints in this case are given in Figure 4. Again for the set point $(\Omega_{CV_2}>0)$, or in temporal constraint terms $(\omega_{CV_1}=1)$, all the arcs are active and behavior of the processes are:

$$\begin{array}{ll}
BF_{P_2}= & \{(\Omega_{CV_2}>0)\rightarrow(U_1>0)\rightarrow\quad(0<F_{out/T_2}\le F_{(out/T_2)max})\rightarrow\\
& \quad(F_{out/T_2}=F_{(out/T_2)max})\quad\}
\end{array} \tag{17}$$

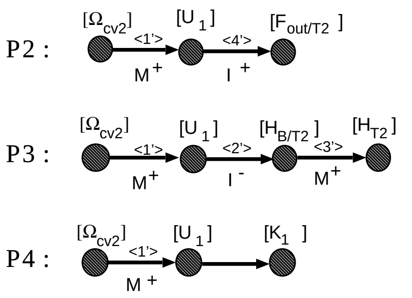
$$BF_{P_3}=\quad\{(\Omega_{CV_2}>0)\rightarrow(U_1>0)\rightarrow(H_{(T_2)min}\le H_{T_2}<H^o_{T_2})\rightarrow(H_{(T_2)min}=H_{T_2})\} \tag{18}$$

$$BF_{P_4}=\quad\{(\Omega_{CV_2}>0)\rightarrow(U_1>0)\rightarrow(K_1>0)\} \tag{19}$$

When CV_2 is opened, BF_{P_2} indicates that the flow of material out of T_2 (F_{out/T_2}) can increase to its maximum level, and BF_{P_3} indicates that level of material in T_2 decreases to minimum. BF_{P_4} indicates that it helps material transfer to the reservoir tank. In qualitative terms, the effects of CV_2 in the system are:

$$CV_2\quad:\quad\{(F_{out/T_2}=F_{(out/T_2)max})\wedge(H_{(T_2)min}=H_{T_2})\wedge(K_1>0)\} \tag{20}$$

The reason of using CV_2 in the system can be explained in terms of these three: "*CV_2 can ease the flow of material out of T_2, reduce the level of material in this tank and transfer material to the reservoir tank.*"



Dependency constraints		
$< 1' >$	:	$\omega^2_{CV_2}(-\omega_{CV_2} - \omega^2_{CV_2})$
$< 2' >$	:	$u^2_1(-\omega_{CV_2} - \omega^2_{CV_2})$
$< 3' >$	:	$h^2_{T_2}$
$< 4' >$	:	f^2_{out/T_2}

Figure 4. Dependency constraints for Example 2.

4.3. Example 3: Selection of components

Yet another goal of the designer is *'maintaining the level of material in tank T_2, for safety purposes'*. An arrangement of the components that can contribute to this is to be derived. The design specification in qualitative terms is given below.

$$\begin{array}{llllll}
\Gamma & = & (H_{(T_2)Fix} & \leq H_{T_2}) & & \\
{[F_1] = [G_1]} & = & M^+[\Omega_{CV_1}] & 'set' & (\Omega_{CV_1} > 0) & \\
{[U_1] = [K_1]} & = & M^+[\Omega_{CV_2}] & 'set' & (\Omega_{CV_2} > 0) & \\
{[S_1] = [E_1]} & = & M^+[\Omega_{CV_6}] & 'set' & (\Omega_{CV_6} > 0) & \\
{[F_{in/T_2}]} & = & M^+[E_1] & 'until' & \Gamma & \\
{[H_{T_2}]} & = & I^+[F_{in/T_2}] & & & \\
{[H_{A/T_2}]} & = & I^-[G_1] & 'when' & \Gamma & \\
{[H_{B/T_2}]} & = & I^-[U_1] & 'when' & \Gamma & \\
{[H_{T_2}]} & = & M^+[H_{A/T_2}] & +M^+[H_{B/T_2}] & &
\end{array} \tag{21}$$

$[U_1]$, $[K_1]$, $[S_1]$ and $[E_1]$ stand for the flow-in and flow-out for CV_2 and CV_6. $[\Omega_{CV_1}]$, $[\Omega_{CV_2}]$ and $[\Omega_{CV_6}]$ denote state variables of the valves. $[F_{in/T_2}]$ is the flow of material into T_2. $[H_{T_2}]$ is the overall level of material in T_2. $[H_{A/T_2}]$ and $[H_{B/T_2}]$ are level of material of type A and B in T_2. $H_{(T_2)Fix}$ is the desired level of the tank T_2. This model is examined for validity. The temporal constraints are given below:

$$\begin{array}{lll}
f^2_1 = g^2_1 & = & \omega^2_{CV_1}(-\omega_{CV_1} - \omega^2_{CV_1}) \\
u^2_1 = k^2_1 & = & \omega^2_{CV_2}(-\omega_{CV_2} - \omega^2_{CV_2}) \\
s^2_1 = e^2_1 & = & \omega^2_{CV_6}(-\omega_{CV_6} - \omega^2_{CV_6}) \\
f^2_{in/T_2} & = & e^2_1(-\gamma) \\
h^2_{T_2} & = & f^2_{in/T_2} \\
h^2_{A/T_2} & = & g^2_1(-\gamma - \gamma^2) \\
h^2_{B/T_2} & = & u^2_1(-\gamma - \gamma^2) \\
(h^2_{T_2} & = & h^2_{A/T_2})or \\
(h^2_{T_2} & = & h^2_{B/T_2})
\end{array} \tag{22}$$

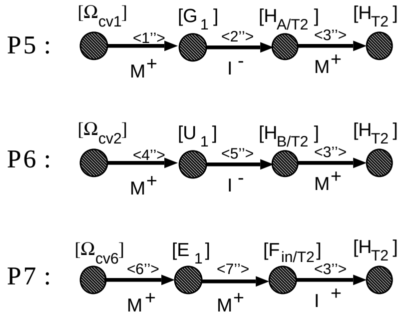
Dependency constraints are shown in Figure 5. In this case some of the arcs in Figure 5 are not active due to the settings. Let's assume that there is no other design preference and verify which of the components are crucial to this arrangement. Deleting CV_6 and the process P_7 implies that the no process will be active when $(\gamma = -1)$. Even if $(\gamma = 1)$, P_5 and P_6 become active and simulation and cycle detection verify that they both lead to the *EMPTY* function. On the other hand, it can easily be shown that deletion of CV_1 or CV_2 (P_5 or P_6), but not both, can lead to the proper functioning. Therefore CV_1 and CV_2 are redundant for the given function. Let's add another preference that the level of B-liquid should not exceed a given level (in order to ensure that A-liquid cannot leak to the next tank). This adds the following expressions to the model (21).

$$\Theta \;=\; (H_{B/T_2} \;\leq\; H_{(B/T_2)lim}) \tag{23}$$

$$[H_{B/T_2}] \;=\; \{I^-[U_1] \;\; 'when' \;\; \Gamma\} \;\; 'until' \;\; \Theta \tag{24}$$

Additional temporal and dependency constraints are:

$$h^2_{B/T_2} = u^2_1(-\gamma - \gamma^2)(-\theta) \tag{25}$$



Dependency constraints		
< 1" >	:	$\omega^2_{CV_1}(-\omega_{CV_1} - \omega^2_{CV_1})$
< 2" >	:	$g^2_1(-\gamma - \gamma^2)$
< 3" >	:	$h^2_{T_2}$
< 4" >	:	$\omega^2_{CV_2}(-\omega_{CV_2} - \omega^2_{CV_2})$
< 5" >	:	$u^2_1(-\gamma - \gamma^2)$
< 6" >	:	$\omega^2_{CV_6}(-\omega_{CV_6} - \omega^2_{CV_6})$
< 7" >	:	$e^2_1(-\gamma)$

Figure 5. Dependency constraints for Example 3.

$$u^2_1(-\gamma - \gamma^2)(-\theta) : [U_1] \rightarrow I^- \rightarrow [H_{B/T_2}] \tag{26}$$

Here when Γ is true ($\gamma = 1$), the process P_6 becomes active and P_7 is inactive. This ensures the level will be maintained. But P_5 can be active only when Θ is false ($\theta = -1$). Only in such case, it can help P_6 to regulate the level of material in T_2. Now the valves CV_1 and CV_2 contribute to the functionality of the system in different ways and cannot be deleted from the design. This example clearly shows that how additional goals of the designer can be incorporated in the model and how they affect the decisions.

5. A QFF-BASED TOOL FOR ENGINEERING DESIGN

QFF is implemented in the experimental design system, QFF2, focusing on automating design verification by shifting the decisions and modifications to the higher design levels. QFF2 is composed of: (1) a data translator for converting specified device model to frame data structure and vice-versa; (2) an implementation of QFF algorithm along with a qualitative simulator, customization and learning modules; (3) domain-oriented library of component models that is used for selecting a proper device model and customizing it; and (4) a window-based user interface that allows a user interactively select arrangement of components, and view simulation results. Fig. 6 shows an overview of the experimental QFF2 system.

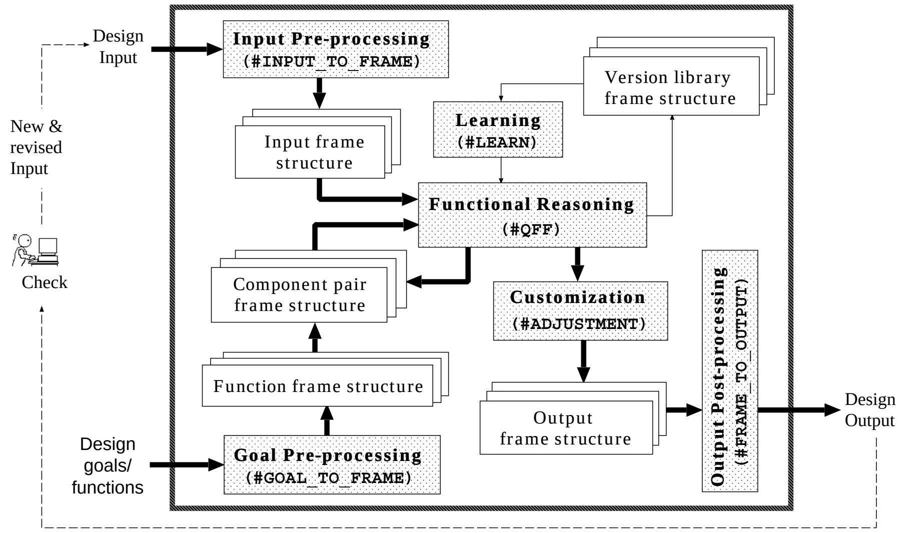
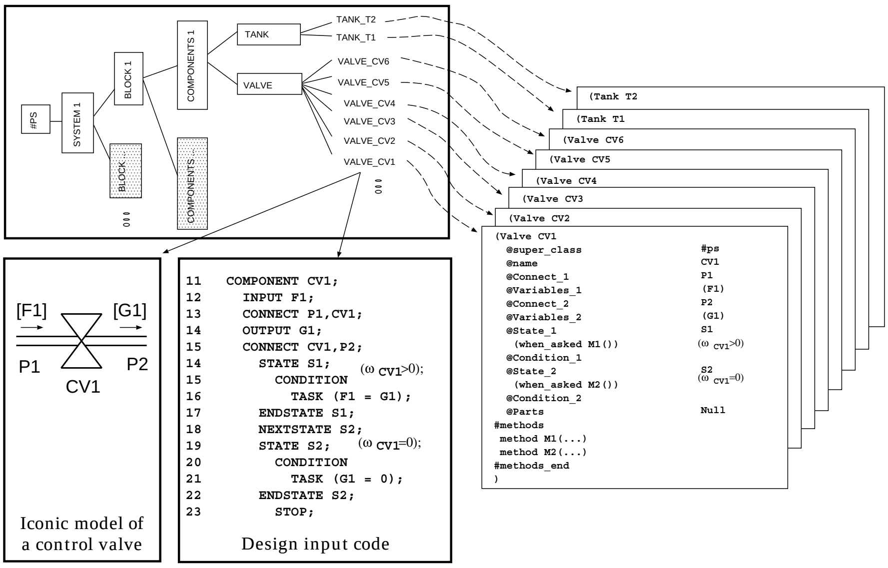


Figure 6. An overview of the experimental design system QFF2.

A designer prepares an initial design sketch using defined components. Simple graphic symbols are designed to ease this step. The initial design input is converted to a frame structure, suitable for processing by the QFF2 system. The `#INPUT_TO_FRAME` module is used for parsing and converting the design input to the frame structure suitable for processing by the QFF2. Presently, a set of pictorial elements are designed to represent some frequently used components in chemical industry, such as valve, tank, etc. This set can be extended if required.



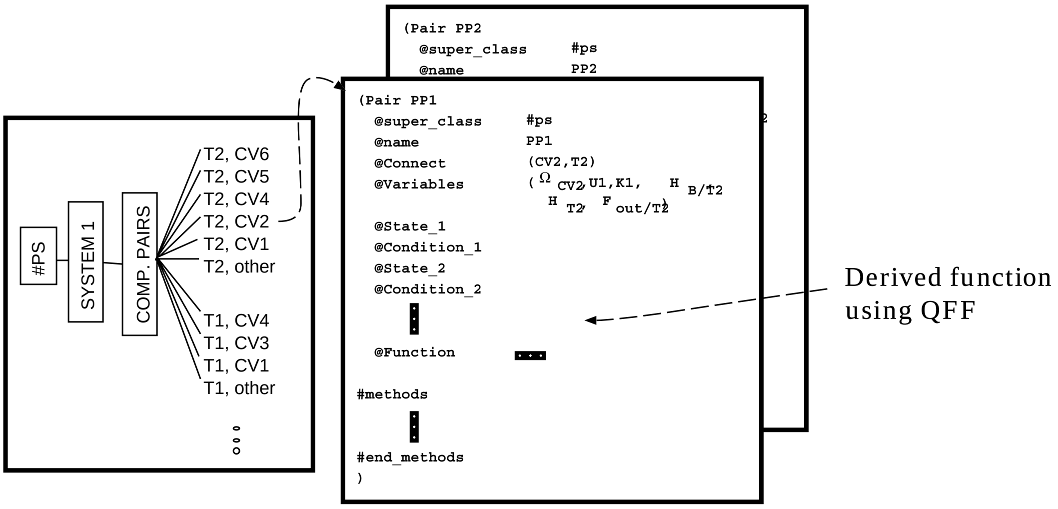
```
(Valve CV1
  @super_class                 #ps
  @name                        CV1
  @Connect_1                   P1
  @Variables_1                 (F1)
  @Connect_2                   P2
  @Variables_2                 (G1)
  @State_1                     S1
   (when_asked M1())           (ω cv1>0)
  @Condition_1
  @State_2                     S2
   (when_asked M2())           (ω cv1=0)
  @Condition_2
  @Parts                       Null
#methods
 method M1(...)
 method M2(...)
#methods_end
)
```

```
COMPONENT CV1;
   INPUT F1;
   CONNECT P1,CV1;
   OUTPUT G1;
   CONNECT CV1,P2;
      STATE S1;       (ω cv1>0);
         CONDITION
            TASK (F1 = G1);
      ENDSTATE S1;
      NEXTSTATE S2;
      STATE S2;       (ω cv1=0);
         CONDITION
            TASK (G1 = 0);
      ENDSTATE S2;
         STOP;
```

Figure 7. Frame representation of a component and a design input file.

In QFF2, each component is associated with a frame that embodies the data related to that component, such as its class, name, connections, etc. As shown in Figure 7, a design input file is represented by a structure of such *class* and *instance* frames. The designer also prepares a set of design goals that must be fulfilled by this design sketch. This is processed by the `#GOAL_TO_FRAME` module and converted to a frame structure that is used by the reasoning module later.

The `#QFF` module stays as the core of the QFF2. There are already two set of frames for the input file and design goals. The `#QFF` module is responsible for checking the input frame structure, preparing component pairs, deriving their function and examining them against the design goals. The pairs that satisfy design goals are recorded in the component pair frame structure. Figure 8 shows frame representation for a component pair. This is done repetitively until all design goals are satisfied.



```
(Pair PP2
  @super_class     #ps
  @name            PP2
```

```
(Pair PP1
  @super_class     #ps
  @name            PP1
  @Connect         (CV2,T2)
  @Variables       (Ω CV2, U1,K1,  H B/T2
                     H T2, F out/T2)

  @State_1
  @Condition_1
  @State_2
  @Condition_2

  @Function

#methods

#end_methods
)
```

Figure 8. Frame representation of a component pair.

The `#LEARN` module keeps record of the design steps. This is necessary for saving time in similar design cases.

The result of reasoning and detailing is then delivered to the `#ADJUSTMENT` module that is responsible for customizing the candidate components. This is the most time consuming task of automatic design because every single slot of a candidate frame must be checked and all the newly created frames must be accounted for.

Finally, the results detailing and customization are recorded in the created frame structure which is finally converted to a final design sketch using the `#FRAME_TO_OUTPUT` module. The designer can check and modify the results, interactively.

6. CONCLUSION

This paper places functional reasoning (FR) in the context of other common sense theories by putting together the results of diverse FR researches in a variety of disciplines. Qualitative function formation (QFF), a technique for deriving a function from a qualitative model is introduced. This puts together the viewpoints on qualitative model, behavior and function, allowing systematic derivation of function from structure and behavior. Finally, an implementation of QFF in an experimental design system is introduced. Presently, tool utilization [15] and fault diagnosis [18] systems based on QFF are developed.

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