Functional Reasoning, Explanation and Analysis: Qualitative Function Formation Technique

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Functional Reasoning enables people to reason about the presence and function of components in a device, derive the purpose of the device and explain how it can be achieved. Qualitative Function Formation (QFF) a functional reasoning technique is introduced. Some novel points are extending the common qualitative models to include interactions and timing of events, by defining temporal and dependency constraints, and binding it with the conventional qualitative simulation. A function concept is defined as an interpretation of either a persistence or an order in the sequence of qualitative states, using the trace of the qualitative state vector derived by simulation on the extended qualitative model. QFF offers solution to the functional reasoning problems and is used to generalize and compare the functions of devices.

1 Introduction

A collective view on functional reasoning theories, techniques and systems was presented in [6] and the problems to be tackled were identified. There are four categories of functional reasoning problems [6]:

1. *Identification Problem*: Given a device, explaining its function using the knowledge of the structure and behavior of its component and their organization. Typical works: [9, 4, 17, 5].
2. *Explanation Problem*: Explaining the presence of a component in a containing system in terms of its contribution to the overall function of the system. Typical works: [19, 3, 14].
3. *Selection Problem*: Given a set of components, selecting the proper components that if used together can achieve a desired function. Typical works: [9, 15].
4. *Verification Problem*: Verifying whether an item can exhibit a required function in a given situation. Typical works: [16, 13, 18].

The QFF is based on the following assumptions:

1.1 Functionality in State Transition

A physical phenomena can be explained in terms of *histories* [10] and *episodes* or *states*. Intuitively, the history that leads to a function should display a certain pattern [2]. A basic feature of state representation is that it assigns a certain characteristic to its referred device [12], therefore it is possible to define function concepts with reference to discovery of an order in the state sequence. A function concept is the result of interpreting a persisted state or a discovery of an order in the sequence of states. This is called "*Functionality in State Transition (FST)*". In biological systems persistence is perhaps the most interesting characteristic and is believed to be governed by natural selection law. In designed artifacts other kinds of *order* may also be considered.

1.2 Functionality in Item Pair

There is a question concerning whether function resides in a device or it is an outcome of the interaction between devices. It seems that humans have a data base in which a device is associated with several functionalities. Some of the theories and systems have taken for granted that the function is a property of its source device. However there are certain difficulties in both logical formulation (see for instance [19]) and actual implementation (see [17], etc., for systems based on this assumption). Some other works argue that function can be ascribed to a pair (see for instance [5, 8]). This is called "*Functionality in Item Pair (FIP)*", stating that at least a pair of devices (or components) are required to interact functionally and function concepts can be derived from their combined histories[1] . Without this assumption it is almost impossible to explain how different functions can be attached to a single device using the histories of individual devices and states. QFF is based on these assumptions.

2 Qualitative Function Formation

2.1 Overview

A system structure can be viewed as an organization of finite number of interacting component pairs. Each pair is modeled by a set of expressions relating qualitative variables by the qualitative operations. Each expression of this form embodies the humans' understanding of interaction between devices. This is called modeling with

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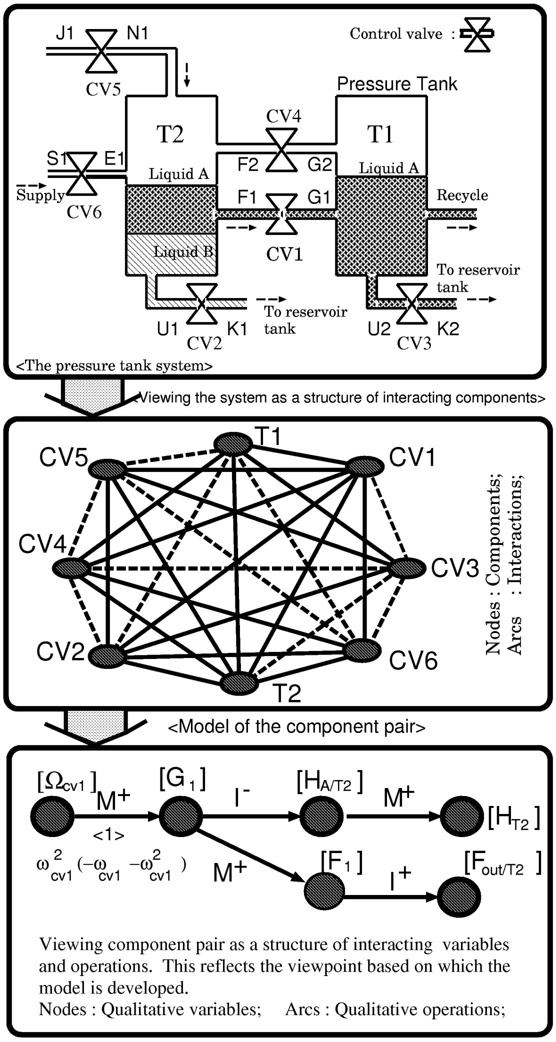
[1] Close ideas are mentioned also by the Locality of Histories [10], Connectivity Hypothesis [8] and Pairwise Interaction of Parts [5]).

Figure 1: Two network models for a device.



reference to conscious observer. Theoretically every two components may be paired, however among all possible interactions, in each case only a limited number of them are actually coded in the model (see Figure 1).

The models of the component pairs are joint together showing the interactions expressed by physical laws as well as interactions representing a kind of coordination. The extended qualitative Model (EQM) is introduced. EQM embodies qualitative processes that *compete* and *cooperate* to realize the system's overall function. Each process relates a characteristic feature of a component pair to the effects it has on the system. Such effects are described by Behavioral Fragments (BFs). The behavior of the pair is given by the history of the qualitative state vector which consists of the landmark values of the variables appearing in BFs of the activated processes. A function concept, for a system embodying a number of qualitative processes, can be expressed in terms of: *Operationality*, i.e. activated processes and their enabling conditions, and *repetition cycle* denoting a persistence or an order in the trace of the qualitative state vector. Figure (2.1) shows overview of the QFF.

2.2 The Method

A qualitative theory of change presumes theories of time and interactions. Physical interactions are represented by ordinary qualitative operations (such as monotonic increase or decrease, etc.). The conventional qualitative model should be extended to embody both the physical and protocol based interactions that are quite common in designed artifacts.

Extended Qualitative Model (EQM) is composed of a set of expressions involving three primitives: qualitative variables and two types of 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 the conventional monotonic increase (M^+), monotonic decrease (M^-) [11], positive influence (I^+) and negative influence (I^-) [7]. Coordinative operations model the protocol based relations and timing. We have found them necessary beacuse in many man-made systms the relation between components are governed by defined protocols rather than pure physical laws.

Definition 2.1 (Extended Qualitative Model) *EQM is a set of expressions of the following form:*

$$[Y] \quad = \quad O[X] \quad 'D' \quad [L_N^i]$$

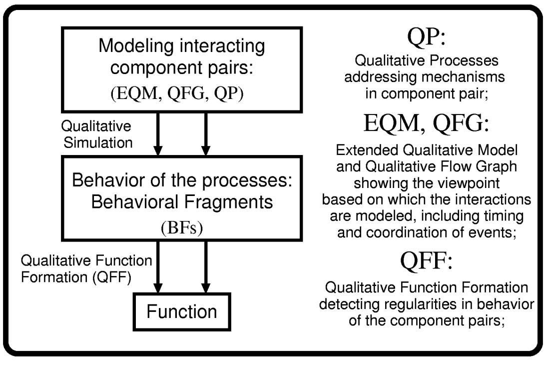
$[Y], [X], [Z]$ and $[N]$ are qualitative variables; O is an ordinary qualitative operation. $O \in \mathcal{O}$, $\mathcal{O} = \{M^+, M^-, I^+, I^-\}$

'D' is a coordinative operation ('when', 'until' *and* 'default'*),*

1. *'when' operation: $[Y] = O[X]$ 'when' L_N^i; implying that $[Y] = O[X]$ only when $[N]$ is evaluated to its landmark value L_N^i.*
2. *'until' operation: $[Y] = O[X]$ 'until' L_N^i; implies that $[Y] = O[X]$ before $[N]$ being evaluated to L_N^i.*
3. *'default' operation: $[Y] = O[X]$ 'default' $O[Z]$; implying that generally $[Y] = O[X]$, but in special cases that $[X]$ is not present, then $[Y] = O[Z]$.*

Y, X and N are qualitative variables; L_N^i is the ith landmark value of N.

Figure 2: Overview of the QFF technique.



In special cases $[N]$ can be a logical variable with only two landmark values evaluated to *true* or *false*.

For each coordinative operation *clock* and *dependency* constraints are defined [1]. Clock and dependency constraints can only be evaluated to one of the followings represented by mod-3 integers, indicating [1]:

present (± 1): two events occur concurrently; *absent* (0): two events do not occur concurrently; *true* ($+1$): an event has occured; *false* (-1): an event has not occured; Table (1) depicts the clock and dependency constraints.

Behavioral Fragment (BF) is the characteristic behavior of a process and is defined as the record of landmark values for the displayed qualitative variables belonging to that process. 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 clock and dependency analysis one can verify which of the arcs of the processes are activated 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.

The repetition cycle is derived for the variables of the qualitative state vector. Qualitative state vector for a component pair is composed of the landmark values of the BFs for displayed qualitative variables of the active processes that model the pair. Note that different cycles can possibly be detected. Each cycle may represent a functional concept from a different viewpoint.

Table 1: Clock and dependency constraints for coordinative qualitative expressions.

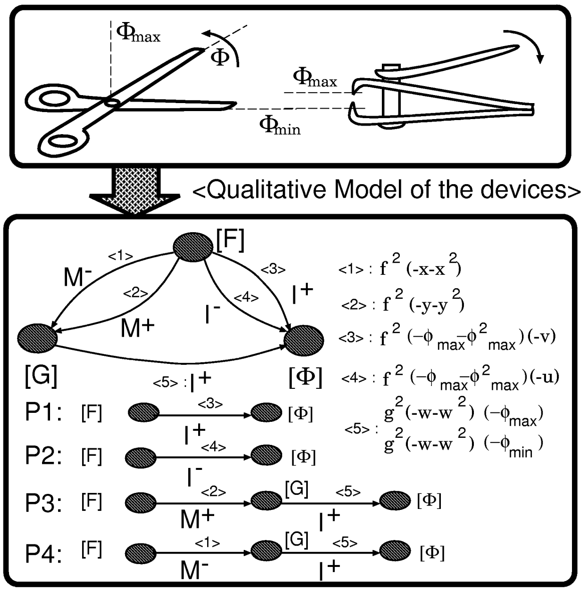
QFF expression	Clock constraint	Dependency constraint
$[Y] = O[X] + O[Z]$	$y^2 = x^2 = z^2$	$y^2 : [X] \rightarrow O \rightarrow [Y]$ $y^2 : [Z] \rightarrow O \rightarrow [Y]$
$[Y] = O[X]$ 'when' L_N^i	$y^2 = x^2 (-n -n^2)$	$y^2 : [X] \rightarrow O \rightarrow [Y]$
$[Y] = O[X]$ 'until' L_N^i	$y^2 = x^2 (-n)$	$y^2 : [X] \rightarrow O \rightarrow [Y]$
$[Y] = O[X]$ 'default' L_N^i	$y^2 = x^2 + z^2 \ (1 - x^2)$	$x^2 : [X] \rightarrow O \rightarrow [Y]$ $z^2 (1-x^2) : [Z] \rightarrow O \rightarrow [Y]$

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

3 Example: Identifying Similar Functions

QFF can identify similar functions of two structurally different devices: a pair of scissors and a nail clipper, although different in structure, it can be verified that they exploit quite similar processes to realize their functions. Qualitative model for both systems is:

Figure 3: Qualitative model for the pair of scissors and the nail clipper.



$$
\begin{array}{lcllcl}
W & = & COLLIDE & & & \\
S & = & SOFTmaterial & H & = & HARDmaterial \\
U & = & (W \vee \Phi_{max}) & V & = & (W \vee \Phi_{min}) \\
X & = & (W \wedge S) & Y & = & (W \wedge H)
\end{array}
$$

$$
\begin{array}{lcll}
[\Phi] & = & \{I^+[F]'when'\Phi_{min}\} & 'until' \quad U \\
[G] & = & M^-[F] & 'when' \quad Y \\
[G] & = & M^+[F] & 'when' \quad X \\
[\Phi] & = & \{I^+[G]'when'W\} & 'until' \quad \Phi_{min} \\
[\Phi] & = & \{I^-[F]'when'\Phi_{max}\} & 'until' \quad V \\
[\Phi] & = & \{I^+[G]'when'W\} & 'until' \quad \Phi_{max}
\end{array}
$$

Φ is the degree of opening between the two edges and $[F]$ is the net applied force. Φ_{max} and Φ_{min} are the maximum and minimum allowable degree of opening between the edges. W is a variable indicating the collision has happened.

Clock and dependency constraints are:

$$
\begin{array}{lcl}
u & = & w^2 + \phi_{max}^2 - (w + \phi_{max} - w\phi_{max}) \\
v & = & w^2 + \phi_{min}^2 - (w + \phi_{min} - w\phi_{min}) \\
x & = & w^2 - (ws + w + s) \\
y & = & w^2 + (ws - w + s) \\
\phi^2 & = & f^2(-\phi_{min} - \phi_{min}^2)(-u) \\
g^2 & = & f^2(-y - y^2) \\
g^2 & = & f^2(-x - x^2) \\
\phi^2 & = & g^2(-w - w^2)(-\phi_{min}) \\
\phi^2 & = & f^2(-\phi_{max} - \phi_{max}^2)(-v) \\
\phi^2 & = & g^2(-w - w^2)(-\phi_{max})
\end{array}
$$

$$
\begin{array}{lccccc}
f^2(-\phi_{min} - \phi_{min}^2)(-u) & : & [F] & \rightarrow & I^+ & \rightarrow & [\Phi] \\
f^2(-\phi_{max} - \phi_{max}^2)(-v) & : & [F] & \rightarrow & I^- & \rightarrow & [\Phi] \\
f^2(-y - y^2) & : & [G] & \rightarrow & M^- & \rightarrow & [F] \\
f^2(-x - x^2) & : & [G] & \rightarrow & M^+ & \rightarrow & [F] \\
g^2(-w - w^2)(-\phi_{min}) & : & [G] & \rightarrow & I^+ & \rightarrow & [\Phi] \\
g^2(-w - w^2)(-\phi_{max}) & : & [G] & \rightarrow & I^+ & \rightarrow & [\Phi]
\end{array}
$$

There are four processes responsible for the behavior shown in Figure 3. The processes P_3 and P_4 depict the collision mechanism and P_1 and P_2 show the reversals of the behavior. When a collision with an external object occurs, if the object is hard, the process P_3 becomes responsible for generating the behavior. On the other hand, if the material is soft, the edges can pass through it and the process P_4 will be active. The arc $[G] \rightarrow I^+ \rightarrow [\Phi]$ of P_3 or P_4 can be active when a collision happens either on the rising or the falling edge of Φ. In case of hard material, simulation shows two possible behaviors and the following cycles in behavior are detectable:

$$\Phi_{max}, \;\; \Phi_{min} < \Phi < \Phi_{max} \tag{1}$$

$$\Phi_{min}, \;\; \Phi_{min} < \Phi < \Phi_{max} \tag{2}$$

Similarly, in case of soft material two cycles are:

$$\Phi_{min}, \;\; \Phi_{max}, \;\; \Phi_{min} < \Phi < \Phi_{max} \tag{3}$$

$$\Phi_{min}, \;\; \Phi_{min} < \Phi < \Phi_{max}, \;\; \Phi_{max} \tag{4}$$

Obviously, the cycles for the behaviors are not identical, indicating that the system functions differently due to certain interactions with the external objects. (1) and (2) indicate that a collision happens on the closing and opening the edges, respectively, but the material is hard and the edge cannot pass through it. (3) and (4) also indicate collision when closing and opening, respectively, but the edges can pass through the soft material. If a collision happens when $[\Phi]$ is falling, and the material is soft, then the cutting function is realized., defined by (3). It is visible that the behaviors and dependency constraints for the nail clipper and the pair of scissors are identical, the functions for both can be defined similarly and the two belong to the same class of devices having the function CUT.

4 Conclusion

Qualitative function formation technique is a general method for deriving the function from the qualitative behavior. Some original contributions of this work are: Extending the common qualitative models to include interactions and timing of events by defining temporal and dependency constraints, and binding it with the conventional qualitative simulation. Defining function concepts as interpretations of either a persistence or an order in the sequence of states, using the trace of the qualitative state vector derived by qualitative simulation on the extended qualitative model. Providing solution to some of the functional reasoning problems and suggesting a method for generalization and comparison of functions of different devices.

Besides function formation, function operationalization, functional design, action planning, resource allocation, tool utilization, categorization, learning and fault diagnosis are other areas of research that should take advantage of the functional reasoning methods in general and QFF in particular. Some other applications of QFF are presented in [6].

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