Qualitative Reasoning and Conceptual Design with Physical Features

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1. Introduction

1.1. Conceptual Design with Physical Features

In design of a new mechanism, the first task of the designer is to decide the principal behavior and structure of the design object satisfying the required function. This phase of design is called conceptual design. The designer's interest in conceptual design is the qualitative behavior and structure. The designer builds qualitative models and evaluates them against the specification. For instance, in conceptual design of a motor, the designer may conclude from the specification that the shaft must be supported, that the motor needs to transform electric energy into a magnetic force, and that it also needs to transform the magnetic force into a moment of force around the shaft. The principal behavior and structure consist of such physical phenomena and entities. Simulation of the behavior may reveal that the motor has a dead point. This leads to the next step of design to avoid the detected problem.

An intelligent CAD (Computer Aided Design) system is expected to assist the designer in conceptual design. The designer knows a number of combinations of available physical phenomena and entities. The designer searches through them for the most suitable physical phenomena for the intended behavior. This search can be assisted by a CAD system with a library of known physical phenomena and entities. We call a combination of physical phenomena and entities a *physical feature* [4], where a feature implies an element of the model of the design object. Conceptual design with physical features is a cooperative task between the designer and a CAD system. The designer selects physical features from the library to compose the behavior and structure with them. The system simulates the behavior of the design object. The result gives the designer information about discrepancy between the behavior and the specification, unexpected physical phenomena and conditions necessary to be satisfied.

1.2. Representation of Physical Features

A physical feature consists of physical phenomena and entities. It means that representation scheme of physical features must be capable of representing individual physical phenomena, entities, and their relationships. For this reason, we utilize Qualitative Process Theory[2] proposed by Forbus as the representation framework of physical features. *Individuals* of Qualitative Process Theory are used to represent mechanical entities. *Individual views* are used to represent combinations of entities and conditions that hold among the entities. *Processes* are used to represent physical phenomena and their influences. Parameters of individual views and processes represent qualitative states of the behavior. Each individual view and process have a set of other prerequisite individual views and processes. An instance of an individual view or a process is created when its prerequisites are found and they satisfy the specified conditions. Individual views and processes are causally correlated by means of their prerequisites.

A physical feature is represented by a combination of instances of individuals, individual views, and processes. The behavior of the design object is composed from physical features by means of unifications between individuals, individual views, and processes. A unification between individuals makes two physical features appear on the same entity. A unification between individual views or processes results in making a new causal dependency. The result of physical feature based design is a model of the qualitative behavior consisting of a causal network among individuals, individual views and processes.

2. Qualitative Reasoning in Physical Feature Based Design

2.1. Behavioral Description

After designing with physical features, the design object consists of individuals and their relationships in addition to individual views and processes. Individuals and their relationships represent how the design object is configured. We call the combination of the individuals and their relationships *structure* of the design object. The behavior of the design object can be deduced from the structure by qualitative reasoning. In investing the behavior, the designer is interested in a specific aspect of physical phenomena. Thus, the attention is paid to specific physical phenomena, whereas the rest is ignored. For instance, the behavior of the motor can be examined from two aspects, viz. the mechanical aspect and the electromagnetic aspect. If the mechanical aspect is of interest, the motor is viewed as an object consisting of a shaft, a pair of electromagnetic coils, and a pair of permanent magnets. Physical phenomena such as *push* and *pull* between the coils and the magnets, *generation* of a moment of force around the shaft, and *rotation* of the shaft are considered in this aspect. On the other hand, seen from the electromagnetic aspect, the motor consists of two electromagnetic coils connected to a commutator. The commutator alters directions of the electric currents through the coils as the shaft rotates. Fig.1 depicts the two aspects of the motor.

If the mechanical aspect of the motor is modeled, details about physical phenomena related to the electromagnetic aspect are concealed, and only the influences from them to the mechanical aspect are considered. The behavior of the commutator is modeled by its influences to physical phenomena relevant to the mechanical aspect. Thus the commutator is considered that it alters poles of the electromagnetic coils in accordance with the angle of the shaft. The deep mechanism

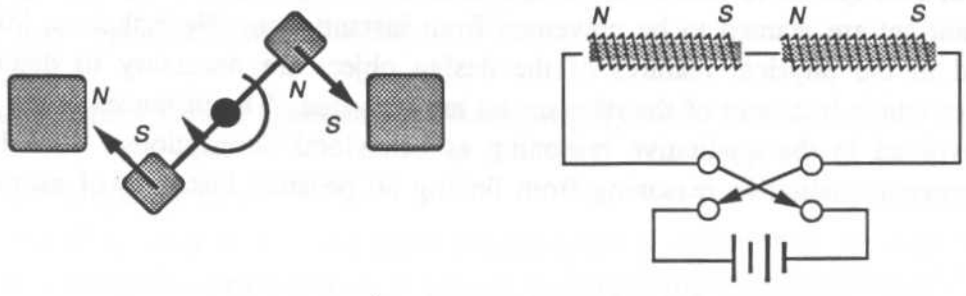

Fig.1. Mechanical and electromagnetic aspects of a motor

of the effects is not considered. In the same way, the model of the electromagnetic aspect ignores details of the mechanical aspect. Therefore qualitative reasoning should not treat all the physical phenomena equally. It has to selectively focus on physical phenomena relevant to the interesting aspect. The rest can be treated as an environment of physical phenomena of interest. Although the environment can influence the simulated physical phenomena, it is assumed to always behave as designed.

In qualitative reasoning during design with physical features, we treat this focusing on an aspect in the following way. First of all, we classify individual views and processes into two categories according to the interest. Individual views and processes under the consideration is categorized in the relevant set, and the others are categorized in the irrelevant set. The qualitative reasoning instantiates only individual views and processes of the relevant set, and not the irrelevant set. Irrelevant individual views or processes are possibly referred by instances of the relevant set. Physical features including such individual views and processes are involved in the qualitative reasoning in the form of *behavioral descriptions*.

A behavioral description is a mapping from provided conditions to active instances of individual views and processes. For instance, the behavioral description of the commutator is a mapping from conditions about the angle of the shaft to polarities of the electromagnetic coils. Let θ be the angle, coil1, coil2 be the coils, and N(x), S(x) be physical phenomena such that x exposes polarity N, S. The behavior description is as follows.

$$\begin{cases} 0 < \theta < \pi & \rightarrow \mathrm{N(coil1)}, \mathrm{S(coil2)} \\ \pi < \theta < 2\pi\,(=0) & \rightarrow \mathrm{S(coil1)}, \mathrm{N(coil2)} \\ \theta = 0, \pi & \rightarrow \mathrm{nil} \end{cases}$$

Behind this behavioral description, there are physical phenomena that are causally connecting the angle and polarities. Contacts between the brushes and terminals in the commutator make an electric circuit. An electric current flows through the coils to either of two directions depending on the contact. The electric current produces magnetic fields around the coils. These physical phenomena are found by qualitative reasoning about the physical feature *commutator*. After the qualitative reasoning, the correspondences between the conditions and the necessary physical phenomena are used by the behavioral description. Intermediate physical phenomena are suppressed from the behavioral description.

Behavioral descriptions reduce load of qualitative reasoning. Individual views and processes of the irrelevant set are wanted to be prevented from instantiation. Nevertheless, instances of them included in the physical features of the design object are necessary to determine the condition under which instances of the relevant set are activated. The instances of the irrelevant set can be involved in the qualitative reasoning as behavioral descriptions. Thus behavioral descriptions prevent qualitative reasoning from finding all possible instances of every physical phenomena.

2.2. Qualitative Reasoning with Behavioral Descriptions

Most of methods of qualitative reasoning are interested in deriving chronological state transitions from the given initial situation (e.g. [5]). To make a behavioral description from an output of a qualitative reasoning, however, a single history derived from one initial condition does not suffice. Instead, we need all possible situations about a physical feature. The suitable method for the purpose is that it examines all combinations of prerequisite conditions and deduces consequents from them. For this reason, we utilize Qualitative Process Engine (QPE) [3] built on ATMS[1]. ATMS used by QPE maintains dependencies from prerequisite conditions to individual views, processes and influences. When QPE generates an instance of an individual view or a process, ATMS creates a justification to it from the assumed conditions. The assumptions used by ATMS are values of parameters, relationships between parameters, and conditions among individuals. A qualitative situation is defined by a set of assumptions. Active individual views and processes in a situation are obtained from ATMS by specifying the corresponding set of assumptions.

A behavioral description of a physical feature is generated from a result of qualitative reasoning. QPE derives instances of individual views and processes together with combinations of assumptions under which they become active. A set of derived individual views, processes, and influences are selected as elements of the behavioral description, whereas the others are removed from the ATMS. The behavioral description is actually the result of qualitative reasoning stored in the ATMS, which contains information about which individual views and processes are active under the given assumptions. If a set of assumptions is specified, active individual views and processes are derived by the ATMS. It should be noted that we specify assumptions defining exactly one situation. If assumptions are excess, they contradict each other and do not determine any possible situation. If they are not sufficient, there can be more than one different situations.

A qualitative reasoning about the behavior of the overall design object is also performed by using QPE. From the structure of the design object, it deduces instances of the relevant set. Since prerequisite conditions are treated as assumptions, generation of instances proceeds independently of the truth value of the prerequisite conditions. Existences of individual views and processes belonging to the irrelevant set are represented not in the form of their instances but conditions. Thus an instance which requires elements of the irrelevant set can be created under the assumed conditions about their existences. After all instances of the relevant set has been found, the user can combine the result of the qualitative reasoning with physical features. It is done by specifying correspondences between conditions, parameters and instances of individual views and processes. According to the correspondences, the system asserts justifications supported by the physical features to the ATMS. If an initial situation is given from the user, possible state transitions are derived by referring to the ATMS. The qualitative reasoning about the overall design object is performed in the same manner as generating a behavioral description. Thus a behavioral description can be generated hierarchically.

3. Physical Feature Based Qualitative Reasoning System

3.1. Structure of the System

Based on the discussion above, we have implemented a system for physical feature based modeling and qualitative reasoning. The system is implemented in Smalltalk-80[1]. Individuals, individual views, and processes are represented by the class hierarchy of Smalltalk-80. The system is divided into three parts, viz. the physical feature editor, the modeling workspace and the qualitative reasoner.

(1) The physical feature editor

This module has the physical feature library. It offers an interface for editing physical features. To define a physical feature, the user makes a structure by instantiating individuals and specifying conditions among them. Then the user selects individual views and processes relevant to the physical feature. After that, the qualitative reasoner derives instances of the selected individual views and processes.

(2) The modeling workspace

It offers a workspace where the qualitative model of the design object is built. The user instantiates physical features in the workspace and connect them together. The task of building a model is performed by means of a graphical interface.

(3) The qualitative reasoner

The module performs a qualitative simulation. All possible state transitions are derived from the initial situation. The user can specify the initial situation by choosing values of parameters and true or false for each condition. The result of the simulation is displayed as a state transition graph.

3.2. Qualitative Reasoning of a Motor

To illustrate the system, we use the motor shown in Fig.2 as an example. The motor consists of a shaft, a pair of electromagnetic coils, and a pair of N and S permanent magnets. The polarities of the electromagnetic coils are alternated by two commutators according to the angle of the shaft.

Fig.3 depicts the physical feature editor showing the physical feature *commutator*. The left side of the window is used to build the structure and select individual views and processes relevant to the physical feature. The right side of the window shows the behavioral description of the physical feature. It is shown that the behavioral description of *commutator* can be connected with others by means of unifications at physical phenomenon *pole* and parameter *h*.

Fig.4 depicts the workspace of the modeling workspace. The model displayed in the workspace is the mechanical aspect of the motor. The behavior of the commutator is included in the model as a behavioral description. The circles represent parameters and conditions about the

[1] Smalltalk-80 is a Registered Trademark of Xerox Corp.

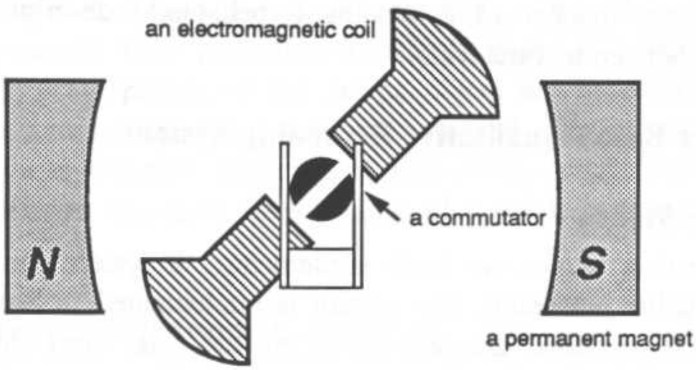

Fig.2. Structure of the motor

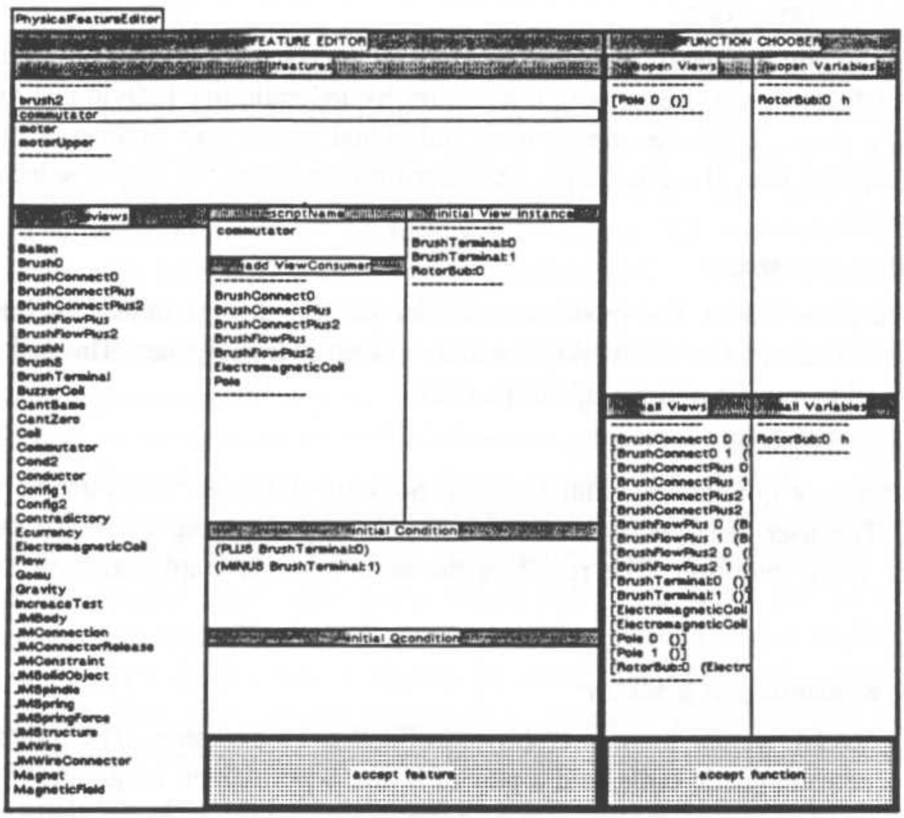

Fig.3. The feature editor

behavior of the motor. The boxes represent the behavioral descriptions of the commutators. The behavioral descriptions are connected to the qualitative model of the motor with links between corresponding parameters (angle h) and individuals (pole and rotor). Polarities of the rotors are determined by the behavioral descriptions. The user selects physical features from the list to build the model of the overall design object.

Fig.5 shows the output of the qualitative reasoner. The motor begins to rotate from the initial situation 1. It visits situations 2 to 5 by turns. Situation 6 is a dead point where the motor does not rotate, because the electromagnetic coils ally with the permanent magnets. Such an unexpected behavior of the design object can be detected by qualitative reasoning.

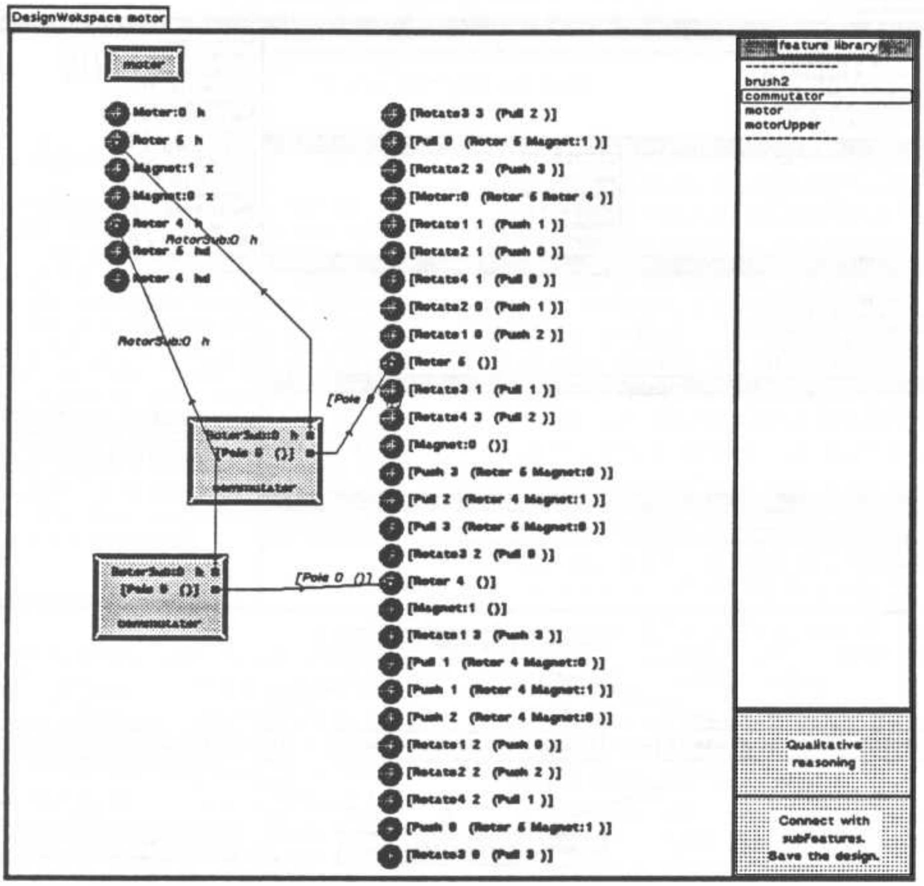

Fig.4. The model of the motor

4. Conclusion

This paper dealt with qualitative reasoning in conceptual design with physical features. Instead of considering all kind of physical phenomena, the designer examines a specific aspect of the design object. In order to simulate the behavior of the specific aspect, we introduced the behavioral description of the physical feature. The structure of the design object is modeled by combining physical features. Qualitative reasoning derives physical phenomena from the structure. Focusing on an aspect is performed by restricting physical phenomena considered by the qualitative reasoner. Behavioral descriptions of physical features allow the qualitative reasoning to ignore the uninteresting physical phenomena and concentrate on the highlighted aspect. A behavioral description of a physical feature is built by using qualitative reasoning about physical phenomena involved in a physical feature. Correspondences between situations and active physical phenomena are calculated from the result of qualitative reasoning. The method is implemented on the basis of QPE with ATMS. When the behavior description is involved in the qualitative reasoning about the overall design object, it directly justifies existences of active individual views and processes from the corresponding conditions. The method can be used to qualitatively simulate the behavior of the design object from multiple viewpoints.

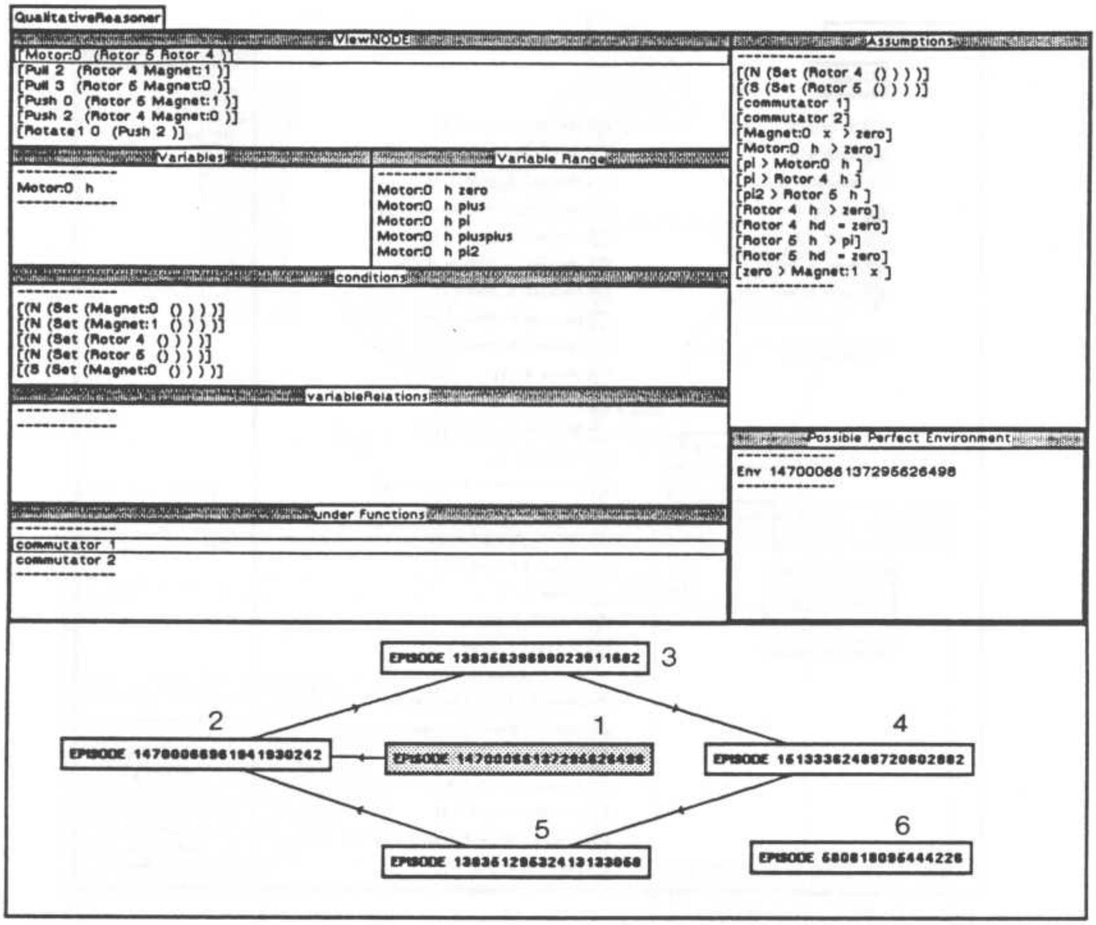

Fig.5. Qualitative behavior of the motor

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